CRANFIELD UNIVERSITY

IGOR GUISASOLA

HUMAN – NATURAL SPORTS SURFACE INTERACTION

SCHOOL OF APPLIED SCIENCES

PhD THESIS

Cranfield University
School of Applied Sciences

Centre for Sports Surface Technology

Doctor of Philosophy

2008

Igor Guisasola

Human – natural sports surface interaction

Supervised by

Dr Iain James

October 2008

This thesis is submitted in fulfilment of the requirement for the degree of Doctor of Philosophy.

Abstract

The playing surface has a great influence on the outcome of a sport. It has a significant effect on the ball behaviour and the technical performance of skills of the sports participants, but it also impacts on their safety. This research is focused on the interaction of humans with natural turf pitches (NTPs). The project research integrates human body, and soil, mechanics in a laboratory environment by means of new technology and methodology to provide new understanding of this interaction.

In a biomechanical study carried out using a portable pitch system, stresses and movements for nine male players performing running and turning movements on sand-based and clay-based NTPs revealed significantly greater peak vertical rate-of-loadings (dF_z^{max}) and peak pressure rate-of-loadings (dP^{max}) for the sand compared to the clay-based condition.

A further soil mechanical study to determine how the dynamic inputs from players affected the behaviour of those surfaces concluded that soil mechanical parameters such as moisture content and dry bulk density have a significant effect on the dynamic stiffness of the surface and that sand-based pitches have a significantly greater intrinsic stiffness than clay-based pitches explaining the observed biomechanical loading rate results.

The research provides a step forward in the attempt to understand how humans interact with sports surfaces and how the surfaces respond. It highlights the importance of the elastic-plastic stress-strain behaviour of soils (or the soil-turf matrix) in response to stresses applied by humans and the difference in mechanical behaviour between sand and clay-based pitches. The findings of this research will inform sports engineers about the advantages of integrating biomechanical and soil mechanical data and lead them to ensure that surfaces that are safe to play and do not hinder the quality of the game by providing reasonable wear resistance, stiffness and traction values.

Cranfield UNIVERSITY

Acknowledgments

I would like to thank the following people,

Helena Suescun, Iñigo Guisasola, Maria Dolores Arenales, Iain James, Victoria Stiles, Ceri Llewellyn, Dick Godwin, Mark Bartlett, Simon Stranks, Mark Dresser, Margaret Boon, James Watson, Sharon Dixon, Stephen Wilson, Phil trolley, Roger Swatland, Kim Blackburn, Paul Wheeler, Jerry Sutton, Sandra Richardson, Colin Mumford, Andrew McLeod, Peter Shipton, Diogenes Antille, Sorche O'keefe, Simon Jeffery, Ana Prada, Borja Arias, Rosa Garcinuno, Irene Mijangos, Pilar Bilbao, Dimitrios Varsamis, Louisa Giannoudi, Catarina Henriques, Athanasios Dedousis, Sarah Tiollet, Pablo Muñoz, Luis Cornejo, Israel Sanchéz, Lewis Beacon, Kerry Pearn, Katie Pendlebury, Jullia Chatterton, Will Temperley, Simon Parsons, Peter Dominek, Lynne Greenard, Jane Clark…

without their help none of this would have been possible. ☺

List of contents

Acronyms

AAB	Artificial Athlete Berlin (Berlin Athlete)
ACL	Anterior Cruciate Ligament
AFL	Australian Football League
ANOVA	Analysis Of Variance
BW	Body Weight
CEC	Cation Exchange Capacity
CIH	Clegg Impact Hammer
DCMS	Department of Cultural Media and Sport
DTI	Digital Transducer Interface
DYNTTS	Dynamic Tri-axial Testing System
ET	Evapotranspiration
FP	Force Platform
FRO	Full Range Output
GRF	Ground Reaction Force
HSDAC	High Speed Data Acquisition and Control Card
IOG	Institute of Groundsmanship
ITF	International Tennis Federation
NTP	Natural Turf Pitch
OM	Organic Matter
PQS	Performance Quality Standards
PSD	Particle Size Distribution
RN	Running
ROM	Range Of Movements
STP	Synthetic Turf Pitch
TN	Turning
USGA	United States Golf Association
WHC	Water Holding Capacity
WRC	Water Release Characteristic
1BFP	Tray immediately Before the Force Plate

Notation

A^{max}	Peak foot contact area (mm^{-2})
$\bar{A}$	Mean foot contact area (mm^{-2})
$\bar{A}_{boot}$	Mean boot contact area (mm^{-2})
D	Constrained elasticity modulus (kPa)
E	Elasticity modulus or Young's modulus (kPa)
F_x	Medial-lateral GRF (kN, BW)
F_y	Anterior-posterior GRF (kN, BW)
F_y^{max}	Peak horizontal GRF (kN, BW)
$(F_y / F_z)^{max}$	Peak ratio between horizontal and vertical GRF
F_z	Vertical GRF (kN, BW)
F_z^{max}	Peak vertical GRF (kN, BW)
G	Shear modulus (kPa)
K	Bulk modulus (kPa)
K_0	Coefficient of lateral pressure
P^{max}	Peak foot pressure ($kN\ mm^{-2}$, $BW\ mm^{-2}$)
P_F^{max}	Peak fore-foot pressure ($kN\ mm^{-2}$, $BW\ mm^{-2}$)
P_R^{max}	Peak rear-foot pressure ($kN\ mm^{-2}$, $BW\ mm^{-2}$)
c	Cohesion (kPa)
dh_z^i	Initial vertical heel impact velocity ($m\ s^{-1}$)
dF_z^{max}	Peak vertical rate-of-loading GRF ($KN\ s^{-1}$, $BW\ s^{-1}$)
dF_y^{max}	Peak horizontal rate-of-loading GRF ($KN\ s^{-1}$, $BW\ s^{-1}$)
dP^{max}	Peak foot pressure rate-of-loading ($kN\ mm^{-2}\ s^{-1}$, $BW\ mm^{-2}\ s^{-1}$)
dP_F^{max}	Peak fore-foot pressure rate-of-loading ($kN\ mm^{-2}\ s^{-1}$, $BW\ mm^{-2}\ s^{-1}$)
dP_R^{max}	Peak rear-foot pressure rate-of-loading ($kN\ mm^{-2}\ s^{-1}$, $BW\ mm^{-2}\ s^{-1}$)
k_d	Secant dynamic stiffness modulus ($kN\ m^{-2}$, kPa)
k_d^{max}	Steady-state dynamic stiffness ($kN\ m^{-2}$, kPa)
p	Mean normal stress ($kN\ m^{-2}$, kPa)
q	Stress difference or the deviator stress ($kN\ m^{-2}$, kPa)
q^{max}	Peak deviator stress ($kN\ m^{-2}$, kPa)
t	Times of occurrence (s)
α	Angle of the plane of failure (deg)
α^i	Ankle joint angle (deg)
α^{max}	Peak ankle joint angle (deg)
ε_a	Axial strain (%)
ε_{max}	Maximum strain (%)
ε^e_{max}	Maximum elastic strain (%)
ε^p_{max}	Maximum plastic strain (%)
ε_s	Shear strain (%)
ε_v	Volumetric strain (%)
θ_m	Gravimetric moisture content (%)
θ_v	Volumetric moisture content (%)
κ^i	Knee joint angle (deg)
κ^{max}	Peak knee joint angles (deg)
ν	Poissons's ratio
ρ_b	Dry bulk density ($g\ cm^{-3}$)

σ	Normal stress (kN m^{-2}, kPa)
σ'	Effective stress (kN m^{-2}, kPa)
σ_a	Axial stress ((kN m^{-2}, kPa)
σ_{max}	Maximum axial stress (kPa)
σ_r	Lateral or radial stress (kPa)
τ	Shear stress (kN m^{-2}, kPa)
ϕ	Angle of friction (deg)
φ^i	Initial foot angle (deg)
$d\varphi^{max}$	Peak foot angular velocity (deg s^{-1})
$d\alpha^{max}$	Peak ankle joint angular velocity (deg s^{-1})
$d\kappa^{max}$	Peak knee joint angular velocities (deg s^{-1})

1. INTRODUCTION AND RESEARCH AIM

1.1. Introduction

The British Government has set the target (DCMS, 2001) to encourage the population to exercise more as a way to increase social inclusion, reduce crime and enable adult exercise to reduce the demands on the National Health Service. This objective is important in the context of this work as an increased rate of participation in sport must not be followed by an increase in the number of injuries from participation in sport.

It is known that the playing surface has a massive influence on the sport outcome. Whether the surface is soft or hard, wet or dry, fully grassed or bare, flat or sloping, smooth or uneven all have a significant effect on the technical performance of skills and the safety of the sports participants. It is therefore necessary to ensure that sports surfaces are not a safety risk to player.

Something that a sport surface must not do is to negatively affect the quality of the game. Hence, safety should be achieved whilst enabling participants to play at the best of their ability. The roll of the ball cannot deviate due to variations in surface quality, and players must be able to judge how far a ball will roll with the strength of a kick. Likewise, when the ball is in the air its landing should be consistent and predictable. The aim of sports engineers is not simply to provide a surface that is attractive to the public but also a surface that allows good play throughout the year and minimises the risk of injuries. Groundstaff have an important management role as a poorly maintained surface can also affect player skills and safety.

It is evident that targets for maintenance and playability will be different for a community-level sports field managed by a local authority than for a Premiership-standard pitch, and this will be a direct consequence of the budget available. However, injury issues are not exclusive to the professional game and therefore any sports surface must be safe to play on.

The demands pointed out above have accelerated the move towards a science-based approach to sports surface design, construction and management that has been slowly occurring in the sports industry for some time.

Present research related to sports surfaces has been focused on the effect of artificial surfaces on the human participant, stimulated by the perception that synthetic surfaces cause more injury to the participant than natural surfaces. Nevertheless, little is understood about how humans respond to a natural turf surface because it is difficult to incorporate natural soil media and sustain turf growth in a laboratory environment. The fact is that each surface has its pluses and minuses, and choosing can be difficult sometimes. However, bearing in mind that the proportion of natural to synthetic surfaces in the UK at present time is around 10:1 (IOG, 2008), research to achieve the above mentioned demands should be carried out on both synthetic and natural sports surfaces to understand the mechanisms behind injury.

This research project is focused on natural sports surfaces and more precisely on the human-natural sports surface interaction, and will provide another step forward in the attempt to understand how to ensure a surface that is safe to play on and would not hinder the quality of the game. The project will overcome some of the challenges previously mentioned by means of new technology and methodology to integrate body and soil mechanics in a laboratory environment to provide new and unique understanding about the interaction between humans and natural sports surfaces.

1.2. Aim and objectives of the research project

The aim of this study is to increase understanding of human-natural sports surface interaction to inform sport engineering about how the use of more sustainable natural surfaces can be improved to provide facilities for increased participation in sport with minimum injury risk.

To achieve the aim of the research, the following key objectives are addressed:

1) To conduct a mechanical characterization of two natural sports surfaces. A high sand content rootzone material used in the construction of natural winter sports surfaces such as modern elite sand construction soccer pitches, and a contrasting clay loam used in the construction of elite cricket pitches and similar to many local authority winter sports surfaces.

2) To measure the stresses applied by human participants and the sensitivity of the human body geometry for two phases of motion: running and turning on the above mentioned natural sports surfaces.

3) To determine soil mechanical parameters for the above mentioned natural sports surfaces in response to the applied stress from the human participant over successive passes for each phase of motion.

4) To integrate soil mechanics and biomechanics data into a conceptual model to inform sports surface engineering and management on how to improve natural turf for maximum usage at minimum risk of injury.

1.3. Thesis layout

The approach taken in this thesis reflects the multidisciplinary nature of the research carried out. Firstly, in relation to Objective 1, Chapter 2 reviews the main current methods of establishing surface properties and to assess human-sports surfaces interactions. This chapter also looks at the incidence and nature of the injuries directly related to sports surfaces.

Next, the initial mechanical characterization performed on the soil media is detailed in Chapter 3. In order to achieve Objective 2, the in-vivo biomechanical study carried out is also described later in this chapter.

Afterwards, based on the results obtained in Chapter 3 and leading to Objectives 3, the soil in-vitro mechanical study conducted is described in Chapter 4.

The relationship between the biomechanical and soil mechanical study is developed in Chapter 5 to achieve Objective 4. Moreover, the contribution to knowledge, together with a full list of publications derived from the present work, an evaluation of the research and recommendations for future work are included in this chapter.

Finally, the conclusions are drawn in Chapter 6.

The research poses the following two questions:

- What are, from a soil science perspective, the effects of the human participant on a natural turf surface and how does natural turf respond to variations in sports movements?

- What are, from a biomechanical perspective, the effects of variations in natural turf properties on human response?

These questions will be developed into research hypotheses and carefully expounded and discussed throughout the course of the thesis following Chapter 2.

This PhD project is a component part of a study funded by the Engineering and Physical Sciences Research Council (EPSRC) under project number EP/C512243/1. The Principal Investigator is Dr Iain James of Cranfield University, with Co-Investigator Dr Sharon Dixon at Exeter University. All research has been conducted by the Author (I N Guisasola), with significant contribution to the design and execution of the project. For the biomechanics experiments, this was in collaboration with Dr Victoria Stiles who was a Post-Doctoral Researcher on the same project.

2. LITERATURE REVIEW

2.1. The importance of natural sports surfaces

Affordable, safe and appropriate sports facilities have been globally recognized to be essential requirements to obtain a healthy nation through sport participation. Within the UK, due to the high urban population density, the maintenance of a natural sport environment has been highlighted as important for the protection of green spaces and playing fields for recreational sport in the community (DCMS, 2001).

As sport has become more popular there has been an increase in the continuous use of Natural Turf Pitches (NTPs) for a number of different sporting activities. However, and particularly at community level, traditional NTPs are subject to accelerated degradation in adverse weather conditions, which negatively affects performance and the safety of players. UK climate conditions include long winter periods where there is little or no grass growth and rainfall exceeds evapotranspiration (ET) from the grass/soil system. This leads to unsatisfactory surface conditions due to excessive moisture in the surface that can affect sport performance, cause severe damage to the surface and compromise player stability and safety.

Sometimes the necessity to reduce the influence of adverse weather conditions to provide an all-year round consistent and durable surface can be fulfilled using Synthetic Turf Pitches (STPs) (Dixon et al., 1999) with significantly more hours of use per week. The use and development of STPs have hugely increased over the last 20 years at both community and elite sport and has focussed on reproducing the playing characteristics of natural turf usually marketed as "Looks, feels and plays like natural grass" (Levy et al., 1990).

NTPs represent the vast majority of sports surface in the UK (Oliver & Casimaty, 1998) and are generally considered environmentally friendly compared to STP (Beard & Green, 1994) or even to agricultural crops (Rodriguez Diaz et al., 2007). Carbon dioxide absorption of NTPs entails a cooling effect that contributes to control pollution (Claudio, 2008). Moreover, the NTP root system is highly efficient in the uptake of applied nutrients as it forms a very dense above-ground biomass that reduces runoff and thus allows time for soil infiltration of water (Green et al., 1991). Consequently, fertilization of NTPs presents a negligible potential for nutrient elements to pass through the root zone into the groundwater or be transported by runoff water into surface waters. This has been confirmed by a number of studies and reviews (Cohen et al., 1990; Gold et al., 1990; Gross et al., 1990).

Another reason that makes NTPs preferable is their nature and properties, which are fundamental to the playing performance characteristics of sports such as soccer, rugby, golf and cricket that cannot be replicated at an elite level using STPs. In cricket for example, pitch properties influence the range of shots played, ball speed and spin characteristics after impact with the surface (Baker et al., 1998) and the progressive deterioration of the pitch as the match goes by influences the balance of the game over several days of play. So whereas it is desirable to reduce temporal variation in most sports, in the case of cricket, temporal variations in surface properties are desirable and essential for the game.

Just as with STPs, the modern NTPs have been developed significantly in the last two decades at both recreational, and to a greater extent, at the elite level of the game. The principal aim in the development of NTPs has been to improve infiltration and drainage of the surface. The drainage of the playing surface must be sufficiently rapid to ensure that the field remains playable at all times. Modern NTPs are constructed from high sand content rootzone materials that minimize soil compaction and allow rapid drainage of excess water and reduced sensitivity of shear strength to increased moisture content (Adams, 1971; Baker, 1991). The result is a favourable environment for turfgrass roots combined with excellent playing conditions, providing more uniform, faster and higher traction surfaces that meet the requirements for the increased player fitness and more advanced technique developed over the same time period. This increases performance by reducing player energy cost but may well imply greater stresses on the player; however, the potentially increased risk of injury from these developments has not been assessed in the literature.

Other consequences of using more freely draining high sand content materials are in terms of environmental sustainability, principally, the increased use of water for irrigation and fertilizers due to lower nutrient retention. In the professional context, such resources are available and necessary to produce the performance and the aesthetic qualities required for television. However, such surface construction materials are not suitable for recreational facilities where these resources are not available. Modifications of these high sand specifications by shifting to finer textured sands and, in some cases, by reintroducing a small amount of clay could reduce water requirements at the expense of drainage capacity and performance (McGown et al., 1997). Moreover, research into new breeding techniques to achieve low-water-use turfgrasses with lower ET rates and superior drought resistance compared to the currently used turfgrass species will further reduce NTPs water requirements (Beard & Green, 1994). These kinds of alternative approaches to providing sustainable turf pitches therefore require further research.

NTPs represent a complex composite living material made of a mixture of soil, grass plants and micro-organisms that is variable in space and time. Soils, themselves, are a mixture of sand, clay and silt particles mixed with water and air. The complex interactions between all these components determine the mechanical behaviour of NTPs. It is known that surface mechanical changes influence performance and can modify the behaviour of, for example, the speed or bounce of a ball under specified conditions (Oliver & Casimaty, 1998). But more importantly, those changes have an effect on the player locomotion system. At the same time, players have an influence on surface wear and degradation that affects players in return.

Therefore, NTPs should not be considered only in terms of the physical conditions that enable the player to perform effectively, but also as a base to minimize excessive stress on the body, by, for example, reducing excessive traction and impact forces, both factors considered to be associated with the cause of injury (Nigg et al., 1986). Unfortunately, research has shown that the functional and safety aspects of sports cannot be optimal in one surface, since the sports and protection functions are not positively correlated beyond a certain point (Kolitzus, 1984; 2003). For instance, a softer surface may provide more comfort to the player, however, ball bounce is compromised. It is a challenge for sports engineering and biomechanics experts to decide where the limit should lie in improving performance without posing unacceptable risks to the player.

2.2. Sports injury aspects

A relatively large amount of research has been published on the mechanical properties of STPs (Bonstingl et al., 1975; Nigg & Yeadon, 1987; Brown, 1987; Valiant, 1990; Dixon et al. 1999; Stiles & Dixon, 2006) compared to research documenting assessment of NTPs (Coyles et al., 1999; Morag & Johnson, 2001; Eils et al., 2004).

Earliest studies based on previous generations of STPs reported them to lead to a higher number of injuries compared to NTPs. A higher stiffness, sliding friction and heat retention from the older generation of STPs has been suggested as the main cause for that. An increased level of impact (James et al., 1978; Light et al. 1979; Cavanagh & LaFortune, 1980; Frederick et al. 1984; Nigg et al., 1986a; Miller, 1990) altering joint movement and muscle activity patterns (Hamill et al., 1992) has been suggested as the mechanisms to increase injury rate (Stergiou & Bates, 1997) however, a direct cause-effect relationship has not been established yet for a particular type of injury.

More recent studies have concluded that no major differences in terms of injury occurrence can be observed between the notably improved third generation of STP and NTP (Fuller et al., 2007; Steffen et al., 2007). A similar study done by Ekstrand et al. (2006) compared injury incidence for soccer players at professional European clubs with third generation STPs, with players from the Swedish Premier League playing on NTPs. It was observed that the most common injuries on both type of surfaces were hamstring, ankle and knee ligament tear and the research concluded that the overall risk of injury on STPs was no higher than on NTPs. Another comparison study between STPs and NTPs properties for soccer by Martinez et al. (2004) took into account anecdotal opinions from players followed by mechanical assessment of the surface properties. The study showed that leg and muscle problems were less frequent on NTPs and that these surfaces were preferred by players perceiving them as more comfortable to play on. Impact reduction was noticed to be higher by the players, compared to STPs, a fact that was supported by mechanical impact test results. A similar preference for soccer played on NTPs compared to STPs was also found by Dick et al. (2003).

The comparison studies available highlight that the playing characteristics and injury patterns on STPs are compared against the bench mark characteristics of NTPs. However, several authors have cited a lack of control over and reporting of NTPs physical properties and maintenance status (Meyers & Barnhill, 2004; Steffen et al., 2007). This makes interpretation of findings complicated because of the varied properties of both natural and synthetic playing surfaces used in different studies. Thus, the available research does not point towards a preferential use of either natural or artificial surfaces with regard to their respective associations with injury occurrence, nor towards a trend of increasing injury on natural turf following recent developments of NTPs.

Impact absorption and traction as cause of injury on NTP

The fact is that, whether or not NTPs yield as many injuries as STPs, injuries still occur on NTPs. In general, evidence of NTPs injury analysis in the literature is sparse. A prospective study on the aetiology of soccer injuries reported that a quarter of injuries were correlated with playing surfaces (Ekstrand et al., 2006). It was assumed that surface features such as uneven playing surfaces, too low impact absorption capacity (referred to as excessive hardness) and inappropriate friction/traction characteristics were connected with injury prevalence.

Surface traction is an important characteristic of playing surfaces that influences player-surface interaction. Without adequate grip players fall over and are unable to perform to a high standard as they cannot stop or rotate rapidly. In the case of excessive grip, players may be exposed to higher levels of resistance to foot rotation than are desirable for their knee and ankle joints (Orchard et al., 2005). Thus, surface traction has been considered a surface characteristic that may be related to non-contact ankle and knee injury incidence (Torg et al., 1974; Milburn & Barry, 1998; Garcia et al. 1999; Orchard, 2002; Livesay et al., 2006). Inappropriate magnitudes of traction can cause the foot to become 'locked' into the surface, transferring force to the ankle and knee (Lees & Nolan, 1998) and so increasing the likelihood of injury occurrence. The concept of injury from high traction was not considered in the past because creating surfaces with sufficient traction for player stability was the principal challenge facing ground staff. This is reflected in the fact that whereas minimum values for traction are, for example, reported in the performance quality standards for soccer (IOG, 2001), maximum values are not included. However, the significant change in mechanical properties experienced by NTPs towards higher stiffness and shear strength highlights the question about how this will influence the player performance and safety.

Several factors that influence surface traction on NTPs, such as grass type and root density have also been described in the literature. For example, Bermuda grass (*Cynodon dactylon*) is suggested to produce greater traction compared to perennial ryegrass (*Lolium perenne*). By the nature of its growth, Bermuda grass contains horizontally creeping stolons which form a surface mesh that increases resistance to wear and also traction compared to perennial ryegrass which is non stoloniferous (Orchard, 2001). The configuration of the shoe sole has also been extensively studied to improve traction. Shorten et al. (2003) concluded that aggressively studded boots were not recommended due to their high resistance to rotation during cutting manoeuvres and subsequent risk of injury particularly of the Anterior Cruciate Ligament (ACL). However, a definitive conclusion regarding appropriate stud length and configuration to minimise injury occurrence has not been reached (Lambson et al., 1996; Carré et al., 2007). Orchard (2001) suggested that modification of the playing surface holds the key to provide players with a universal method of reducing traction and so reducing the risk of injuries related to shoe-surface locking. However, as was mentioned before, any safety modification will affect performance aspects of the surface (Kolitzus, 2003) and so this effect should be also considered when investigation injury prevention.

Surface impact absorption is another important property of sports surfaces. It influences ball-surface interaction and also player-surface interaction. A too-low impact absorption can cause impact related injuries, whether to the leg or the head of players (Dura et al., 1998). A too-high impact absorption implies a greater damage to surface when performing sports (Canaway & Baker , 1993).

Racing horses can also be considered to be elite athletes who interact with NTPs. Horse racing takes place on a variety of NTPs with a range of degree of care and attention being given to the surface quality. It is known that the horse performance and the degree of risk of injury to the horse and rider are influenced by the surface impact absorption capacity (Field, 1994). A 'soft surface' means a slow wet surface while a 'hard surface' represents a fast dry surface with low impact absorption. Thus, a high correlation between race times and impact absorption (measured as hardness) of the racecourse surface was found where race times increased as the surface became softer (Zebarth & Sheard, 1985). Racetracks that are excessively soft complicate horse propulsion through sinkage and sliding, and can cause stress injuries on the horse's hind quarter muscles (Field, 1994). Conversely, hard racetracks imply a high impact force on contact with a horses hoof or jockey head due to a reduced surface deformation or cushioning. This has been suggested to result in a high rate of loading, and therefore strain, experienced by the horse's leg bones, which may lead to micro damage and gradual weakening of the leg bones (Pratt, 1984). Just like human players, horses adapt their musculoskeletal structure to different surfaces characteristics. Non-uniform surfaces are seen as a great potential for the risk of injury occurs when the surface varies from relatively hard to significantly softer over a short distance (Chivers, 1999). It was suggested by Stover (2003) that if the need to re-adapt to a different surface condition is reduced, the potential for injury can be minimized, highlighting the importance of achieving uniformity.

Nigg et al. (1988a) investigated deformation of different surfaces after landing from a jump and also assessed players comfort levels. They found that the surface that exhibited the smallest maximum deformation was the least comfortable. Players felt that the stability of the surface and control of their movements were greater on the stiffer surfaces. Less compressible surfaces were, however, associated with larger forces acting on the body, a fact that could lead to a higher incidence of overloading injuries because the muscles do not have enough time to contract and absorb forces, causing the forces to be transmitted further up the axial skeleton (Fiolkowski & Bauer, 1997). Highly compressible surfaces may increase the energy cost of player locomotion as the energy of the sport movement adds to the energy necessary to deform the surface (Lejeune et al., 1998) inducing a subsequent greater risk of injury by muscle fatigue (Millet et al., 2006). All those findings seem to suggest that there should be an intermediate surface deformation behaviour where a compromise between player stability, comfort and energy efficiency can be met.

Some attention has also been paid to the influence of climatic conditions on parameters such as surface impact absorption and traction and the occurrence of lower-limb non-contact injuries. Orchard et al. (2002) demonstrated a trend for the Australian Football League (AFL) for incidence of ACL injuries on NTPs motivated by changes in weather conditions. The author reported that traction on NTPs was likely to be higher when the ground was hard, dry and the grass cover and root density are at their greatest as in the early part of an autumn-winter season. Other researchers have also suggested that a significant increase in injury rate during the summer season was due to warmer weather where surface drying conditions (ET > precipitation) prevail, with resultant harder surface conditions (Baker, 1991; Hodgson et al., 1998).

2.3. Quantifying player-surface interaction

The correct evaluation of surface related injury risk requires player-surface interaction to be evaluated. This interaction is a complex function of surface mechanical factors and player biomechanical response (both voluntary and involuntary). It is also a two way interaction as outlined in Figure 2.1. The surface appearance and mechanical behaviour modifies player biomechanical response, which in turn loads the surface, resulting in deformation that can change the surface mechanical behaviour and appearance again. This interaction is variable in time and in space due to environmental factors, player stamina and the nature of the sport played.

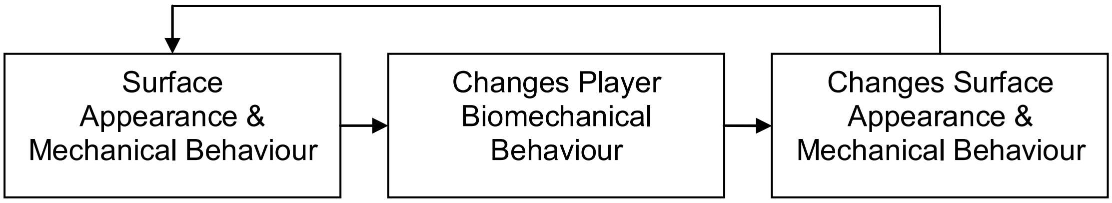


Figure 2.1 Player-Surface interaction outline.

2.3.1. Mechanical testing

In situ measurements

The development of methodologies for testing of surface mechanical properties has mainly been driven by: on the one hand, the need to benchmark STPs performance against NTPs; and on the other hand, the development of Performance Quality Standards (PQS) for the specification and improvement of NTPs. Just as there are two main ball-surface interaction tests (ball roll and ball bounce) in PQS, there are two main player-surface interaction tests: measurement of surface impact absorption and traction (Fleming et al., 2005).

Frictional characteristics

The linear traction equipment used to simulate and measure sliding forces on NTPs usually have a metal studded sled that is weighted and moved in a single direction, while the force required to move is recorded. This test is designed to be analogous to the type of traction required from players when moving and stopping in a straight line. In a similar way, rotational forces can be generally mimicked and measured by a metal disk with several boot studs uniformly spaced and attached to the underside. Once weights are applied, the unit is lifted and dropped from a fixed height and the force that is required to make the disc rotate freely is measured in Nm (Canaway, 1975; Canaway & Bell, 1986). These forces can generally be estimated using linear mathematical models that predict draught force from geometric parameters and physical soil properties (Godwin et al, 2007) although they have not been adapted for the range of stress rates required by human player activity. Nigg & Segesser (1988a) investigated the measurement of linear and rotational traction and showed that the magnitude of normal force to be dragged or rotated hugely influences the final traction outcome. They concluded that using forces less than those created by players could lead to incorrect conclusions about player-surface interactions. This highlights the need to assess the player dynamic inputs before the surface is tested by mechanical means. A number of new engineered devices, such as the Pennfoot apparatus (Lafortune et al., 2003) and Strathclyde Sports Turf Testing Rig incorporate the recording of both linear and rotational tests in one device (Blackburn et al., 2005).

Soil factors such as texture, bulk density and grass rooting may affect traction by influencing soil shear strength. Holmes and Bell (1986) compared a soil based surface against a sand carpet construction method and found that the sand carpet construction gave consistently higher traction measurements than the soil based surface. Canaway and Baker (1993) stated that it is how these soil factors affect water movement and retention and their interaction with wear that largely determine their effect on traction of NTPs. For example, it was shown that traction on rootless soils increases with increasing soil bulk density (Rogers and Waddington, 1990). Scott and Pearce (1976) explained that as soil density increases, soil particles get closer together, this increases the frictional resistance between them and so higher levels of traction will be expected. However, higher soil bulk densities are associated with the areas of greatest wear (with a lack of grass cover) and penetration resistance, potentially reducing stud penetration and therefore presenting lower traction values (Baker, 1991).

Cushioning characteristics

Test devices for measuring impact absorption use instrumented bodies with predetermined mass dropped from a specified height (Young & Fleming, 2007). The Clegg Impact Hammer (CIH) was developed by Clegg (1976) in Western Australia for testing road base surfaces and is becoming the preferred method for assessing impact absorption of NTPs referred to as surface hardness. With the CIH, an accelerometer is mounted on a missile (0.5 or 2.25 kg) which is dropped from a set height (55 cm or 45 cm respectively) through a guide tube. On contact with the surface, the missile is decelerated and the peak deceleration value in gravities (g_{max}, simply known as G) is provided. Surfaces with a low impact absorption capacity or cushioning (often termed 'hard surfaces') cause greater deceleration and thus the G figure is higher than other surfaces with higher impact absorption capacity ('softer surfaces'). Rogers and Waddington (1990) discovered that the use of the 0.5 kg missile can be strongly influenced by the amount of grass cover and that the larger 2.25 kg missile eliminated the effect of vegetation and gave a better indication of the whole surface cushioning, measured as hardness. The same authors attached a data logger to the CIH to measure not only the maximum deceleration rate of the dropped hammer but also the time to peak deceleration and the impact duration. A high correlation between maximum deceleration rate and both the time to the peak and duration of impact was found, suggesting that the surface could be characterised using only one of these criteria. This suggests that even simple CIH equipment, providing peak deceleration data, could be used for surface mechanical testing.

The Artificial Athlete Berlin (AAB) is another drop test apparatus used to measure surface impact absorption. Unlike the CIH which is lightweight, the AAB uses a 20 kg dropping mass that is released from a height of 55 mm onto a spring and test foot. The spring compresses and therefore introduces a degree of compliance to the system that yields a contact time between the load cell and the testing surface of 0.1 – 0.2 s. This contact time acts to imitate a typical foot ground touchdown contact time of an athlete when performing many sporting movements. This device measures surface deflection and peak impact force, which is converted into a percentage indicating the reduction in force of the test surface in comparison to an impact measured using a concrete test surface. The deflection is used to give a measurement of surface stiffness and the percentage reduction in force is used to quantify mechanical energy loss and the level of surface cushioning (Nigg & Yeadon, 1987). Young & Fleming (2007) observed that the deflection of some NTPs can be greater than the range for this device and that the specification of the concrete used as the reference base also affects the final result and so that this data should be included when using the AAB.

Just like surface traction, surface impact absorption also depends on parameters such as soil texture and bulk density, water moisture content and grass cover. Richards and Baker (1992) found a general tendency of increased impact absorption with increasing grass length via a CIH. Holmes and Bell (1986), using a 0.5 kg CIH device, demonstrated that sand based NTPs gave almost identical hardness readings to soil based NTPs, however, the soil based NTPs exhibited greater variability. In another study, the same authors concluded that CIH readings reduced as moisture content increased caused by a greater surface deformation, although sand based rootzones do not exhibit such a marked decline compared to rootzones containing soil The authors did not supply an explanation as to why that happened but as stated by Oliver & Casimaty (1998), sand textured soils usually exhibit a greater resistance to compaction on a short-term basis and less strength sensitivity to moisture thus the uniformity within these surface is usually greater compared than in less sandy soils.

These mechanical tests provide the basis to characterize the playing quality of a surface, often termed ‘playability’; however they represent simplifications of the player-surface interaction. In these tests, the surface is usually stressed in only one fixed direction using either constant velocities or dynamic loads applied from constant heights to maintain constant energy. However, real loads from players are variable during the movement, from subject to subject and within subjects over time (Dixon et al., 2000). Nigg (2003) examined the range of equipment commonly used for surface mechanical testing and concluded that while measurements can be made that describe material aspects of a sports surface, they cannot be used to predict external or internal forces acting on the athlete’s body and so injury potential. He emphasized the importance of using biomechanical testing to correctly quantify input conditions experienced by the player’s locomotor system during ground contact in order to understand fully the possible link with overuse injury phenomena.

Laboratory measurements of NTP behaviour

A better approach to quantify the mechanical parameters of NTPs can be performed making use of more sophisticated methodologies and equipment that currently require working in a laboratory environment (as will be explained further in Chapter 4). Loading or stressing an NTP produces a subsequent deformation or strain that is a function of the interaction of all the components comprising the NTP. Soil can be considered the basic component of NTPs and so, as a first approximation to this complex problem, mechanical characterization of NTPs can be evaluated in terms of the soil mechanical behaviour, which is actually a function of the soil texture, soil dry bulk density and water moisture content (Whitlow, 2001). A precise characterization of this stress-strain behaviour is essential to quantify both ball-surface and player-surface interactions, affecting for example ball bounce, player movement and surface compaction.

Classical approaches to determining soil mechanical properties for civil and agricultural engineering are based on quasi-static testing to assess soil mechanical parameters such as shear strength that emphasize the plastic behaviour of soils (Carman, 2002; Spoor et al., 2003). For these soil mechanical disciplines, elastic deformation only occurs at very small amounts of strain and is normally negligible. However, stress-strain behaviour of soils is highly strain rate dependent (Horn, 2004), which means that the final strain is a function of the rate at which the soil has been stressed. Traditional quasi-static soil testing such as uni-axial and tri-axial compression testing (Fredlund et al., 1997), involves very low strain rates that allow enough time for the soil to deform through irreversible fracture mechanisms that imply large amounts of plastic deformation (Ashby, 1978). However, as the stress is applied more quickly to the soil, the time to deform reduces and the overall soil strength increases as a result.

Soil mechanical stress-strain behaviour is known to be a visco-plastic, in that is partly elastic or reversible in time if the load is removed and mainly plastic or non-reversible (Yin & Graham, 1999). The limits and relative proportions between the elastic and the plastic behaviours depend on the strain rate at which the soil is deformed, which is a function of the load magnitude and the rate of loading (Karmakar & Kushwaha, 2005). It is believed that the inputs from sport players introduce a whole new range of high strain rates that will hugely affect classical soil mechanical response predicted by parameters such as shear strength (Wulfsohn et al., 1999). Player dynamic inputs will make soil elastic deformation become as relevant as plastic deformation or compaction in understanding the overall mechanical behaviour of NTPs. For example, greater strain rates could imply greater elastic recoveries and thus higher impact absorption properties. Some updated mechanical parameters that enable quantification of both elastic and plastic dynamic behaviour of soil simultaneously are proposed in the literature (Schneider et al., 1999).

This analysis requires traditional soil mechanical testing equipment to be updated to work with very high strain rates and so it becomes prohibitively expensive compared to the previously mentioned ‘portable’ equipment. In turn, they allow mimicking of player inputs, in terms of loads and loading rates, and determination of more fundamental parameters that will finally predict traction and impact absorption for a variety of NTP compositions.

2.3.2. Biomechanical testing

Biomechanical testing characterizes the stresses applied by players on the surface (kinetic analysis) and the way the movements are performed by the players (kinematic analysis). Players are by no means the same as each other and a quantitatively identical performance is impossible even within subjects, which makes the assessment of players very complicated to assess (Kolitzus, 2003) and the adoption of strategies such as high replication and participation of high number of subjects are compulsory.

Kinetic assessment

The determination of ground reaction forces is useful to provide information on the characteristics of a given movement. The Ground Reaction Force (GRF) of a running step was stated by Miller (1990) as 'the force that reacts to the push transmitted to the ground by the foot of the runner'. He explained that GRF represents the acceleration of the whole body centre of gravity and although lower limb contributions are important, they are not the only contributions made to the total body acceleration. According to Miller, the lower extremity acts mainly as a transmitter of the acceleration of the whole body centre of gravity to the ground. This suggests that GRF data may not be a sensitive measure to study lower leg impact as it is not only the accelerations of the lower limb segments that produce GRF values. The collection of GRF data remains useful since it provides information on various performance parameters and external system inputs (e.g. ground contact time and rates of loading).

A force platform is the most common piece of equipment used to measure the magnitude, direction and the duration of the GRF in relation to time (Dychko, 1998). An alternative approach is to measure forces underfoot using insole pressure measurement devices (Challis, 2001). These devices incorporate techniques to measure continually forces between the subject and shoe, without the need to contact a marked area of the ground; targeting specific areas for contact can lead to changes in gait when running (Nigg et al., 1986b) – this issue will be considered in more detail in Chapter 3. While the analysis of force under regions of the foot can be done with the data collected from pressure insoles, the analysis of pressure within different anatomical areas of the foot is also commonly undertaken (Dixon & Stiles, 2003). More detailed information about these technologies is provided in Chapter 3.

A strong association between peak impact variables (magnitude and loading rate) and the occurrence of overuse injury in running has been pointed out (Nigg et al., 1986a; 1988b; Miller, 1990; Shorten, 2000; Shorten & Himmelsbach, 2002). McMahon and Greene (1984) explained that cushioning works to decrease the forces between colliding bodies by increasing the time of collision. For example, the magnitudes of peak impact forces collected during running from barefoot have been shown to reduce with the use of a shoe, which has led to the belief that the magnitude of the impact peak is influenced through the shock absorbing ability of the shoe (Rodano, 1983). The same logic was applied to studying the influence of surface cushioning on impact force variables and therefore the influence of commonly held associations between sports surface cushioning and the occurrence of injury (Dixon et al., 2000).

However, contradictory to the findings of Dickinson et al. (1985), peak impact forces have been found to remain constant while running both with and without shoes while peak rate of loading increased without the shoe (De Wit et al., 2000). Note that in this study, initial foot angle with respect to the horizontal was reduced for the barefoot condition compared to the shod condition. The researchers explained the similarity between impact magnitudes as a result of compensatory changes in initial rear-foot angle. In a similar manner, peak impact forces have been maintained with changes in surface (Nigg & Yeadon, 1987; Dixon et al., 2000; Dixon & Stiles, 2003; Nigg et al., 2003). What is clear is that the influence of changing shoe and surface conditions on force characteristics during player analysis is not fully understood.

Kinematic assessment

The movement of the player is constantly and smoothly adjusted by complex control mechanisms involving the nervous, muscular and skeletal systems of the body (Vaughan et al., 1992). Devices that perform visual recording of the position of body segments are used to digitize body motion in three-dimensional coordinate space. Assessments of running on surfaces with different levels of shock absorption have revealed maintenance of impact force peaks at a constant value (Nigg and Yeadon, 1987). Literature seems to suggest that player nature allows for adjustments in leg collision geometry based on feedback mechanisms that are suggested to regulate impact forces for maintaining acceptable levels of impact (Dura et al., 1999; Dixon et al., 2000).

For example, with reference to Figure 2.2, evidence of higher knee flexion and knee flexion velocity prior to ground contact during running has been suggested to indicate greater lower leg system compliance for a less compliant surface (Dixon et al. 2000). A larger angle implies larger leg deformation occurring sooner during an impact phase, increasing the time over which the collision occurs and consequently reducing the peak magnitude of the impact force.

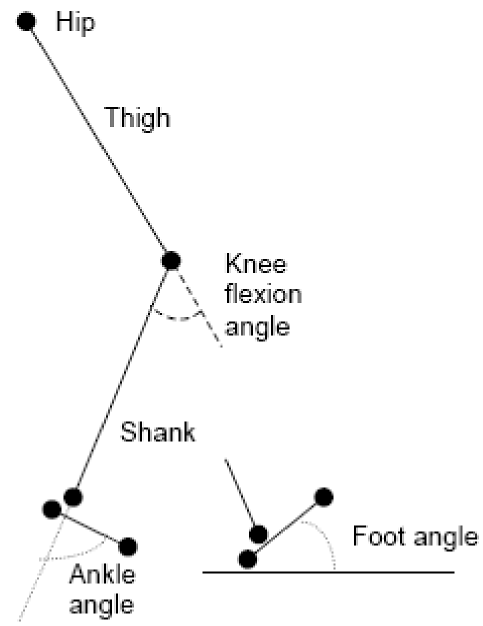


Figure 2.2 Angular conventions of the lower leg.

An analysis of barefoot running compared to shod conditions carried out by De Wit et al. (2000) found that a lower initial foot angle (flatter foot) at touchdown is another a kinematic adjustment to reduce excessive loading. A flatter foot angle (thus increasing the area over which the ground reaction force is distributed) has the effect of reducing the peak local pressure underneath the heel. Interpretation of initial foot angle would be enhanced if combined with the analysis of insole pressure data and contact area during the initial loading phase since high correlation between a flatter foot at ground contact and lower peak heel pressures has been found.

Dixon et al. (1998) reported that a lower heel impact velocity was another method of reducing the collision deceleration, when peak impact forces remained similar when running barefoot on a conventional asphalt surface compared to a rubber-modified bituminous sports surface with 48% more cushioning. In another study, Dixon and Stiles (2003) assessed the cushioning properties of five tennis surfaces during running, with the additional interaction of two different models of tennis shoe. The five surfaces, which varied in International Tennis Federation (ITF) mechanical classification from ‘low’ to ‘high’, were assessed biomechanically using seven recreational tennis players. However, no significant kinetic variable differences were found between the surfaces for either shoe. With regard to peak heel pressure, both shoes ranked the surfaces in the same order with the lowest pressure peak yielded from the surface mechanically categorised as having a ‘high’ cushioning ability. This finding corroborates the mechanical test results. Changes in shoe also yielded significantly different peaks in pressure. The researchers suggested that a change in shoe appeared to be more influential than a change in surface in yielding lower impacts for the range of surfaces tested in this study. This finding emphasises the importance of testing the combination of shoe and surface during mechanical assessments.

A significantly reduced flexor moment about the ankle joint on STPs compared to a baseline condition was observed by Stiles & Dixon (2006) during a typical tennis running forehand foot plant, which was associated with a measured lower initial foot angle on this surfaces compared to the baseline. The findings from this research suggest that a more cushioned surface yields lower magnitudes of joint moment compared to a less cushioned surface. They explained that a lower magnitude of peak moment may have occurred as a consequence of a flatter initial foot angle, and thus a reduced amount of muscular control required by the muscles about the anterior aspect of the tibia to control toe-down. On the harder baseline surface, a higher flexor moment was found together with a higher initial foot angle magnitude. This increase in peak moment on hard surfaces may explain reports of shin problems when running on harder surfaces (Anderson & Reynolds, 2005). Modifications of the peak moments about the knee were found in the same manner by Stefanyshyn et al. (2006), who related higher magnitudes of joint moments with higher injury occurrence.

All the biomechanical adaptation evidence shown above seems to suggest that leg stiffness is actually influenced by the cushioning properties of the surface (Butler et al., 2003). For stiffer surfaces, where there is higher likelihood of encountering high magnitudes of impact force, the joint and thus leg stiffness reduces to maintain an overall level of subject-interface stiffness. Where surfaces are less stiff, stiffness of the supporting limb also accommodates by being stiffer to maintain subject-interface stiffness through muscular adaptations to protect the body (Ferris et al., 1998).

2.3.3. Integrated mechanical and biomechanical testing of NTPs

Player biomechanical assessment of NTP properties using sports specific movements remains a rarity (Dabnichki, 1998). Integrating natural soil media and sustaining turf growth in the laboratory environment complicates research into player interaction with NTPs. An analysis of body and leg accelerations for a variety of surfaces in the field, including both NTPs and STPs, has been performed to assess whether the characteristics of soccer specific movement techniques are adapted for different surface conditions (Brachet et al., 2003). Maximum shank and pelvis acceleration were found to be similar between NTPs and STPs. The authors concluded that the findings were useful indicators of a comparable injury risk across all surface conditions, assuming accelerations are correlated with injury prevalence.

There have been some attempts to site force platforms below NTPs in the field (Smith et al., 2002, 2004) and to measure patterns of foot plantar pressure during soccer specific movements for footwear cushioning testing (Coyles and Lake, 1999; Eils et al., 2004). Tillman et al. (2002) used pressure insoles to compare GRF for asphalt, an STP and an NTP. These authors detected no difference in loading between the tested surfaces, concluding that surface stiffness was not directly linked to injury risk through loading. However, no attention was paid to any possible change in body kinematics that could have been performed by the players to adapt to the different surfaces resulting in a constant load observed. More recently, Ford et al. (2006) compared an STP with an NTP using in-shoe pressure distribution and did observe differences in loading and peak pressures for the two surface conditions for different regions of the foot, showing that effect of surface stiffness is still under debate.

An integrated study investigated the effect of changing a soil surface from a soft to a hard condition by simultaneously measuring pressure distribution within the soil and the shoe when running (James et al., 2006; Dixon et al., 2008). It was found that an increase in the dry bulk density of 1460 to 1590 kg m^{-3} resulted in an increase in g_{max} of 125 to 235 G measured using a 0.5 kg CIH. Peak heel force was significantly lower for the lower density soil condition. Such integrated studies and the use of novel laboratory environments allow the stresses on the player and the surface to be analysed simultaneously (Figure 2.3) and are seen as the way forward to understand player-surface interaction (Dixon et al., 2008).

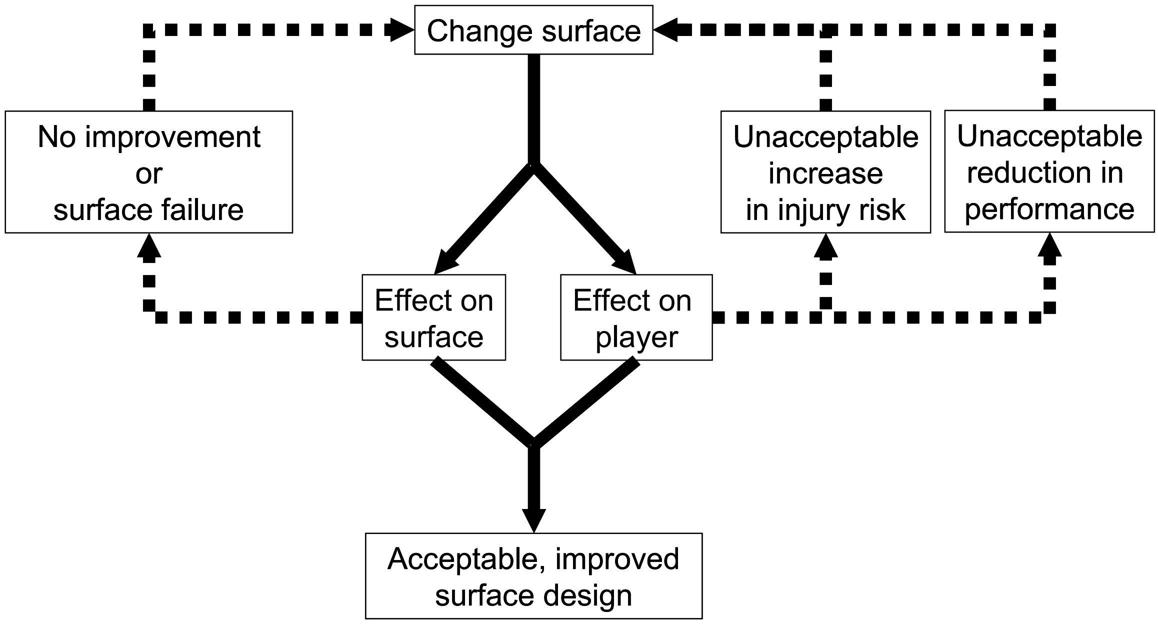


Figure 2.3 A model for integrated development of surfaces. Any change in surface properties should be evaluated in terms of both the effect on the surface and the effect on the player (in terms of injury and performance). The model responds to negative feedback until an acceptable improved surface design can be determined – without detriment to the surface or player. (Also published in Stiles et al., 2008)

2.4. Summary of the literature review

Promotion of a healthy nation can be aided by provision of appropriate sports facilities that can be used more intensively, are affordable by local authorities, and provide high performance and safety for players. In order to achieve that, the player-surface interaction has to be understood. This is a two way interaction, where players load and deform the surface at a certain rate, and where they are also influenced by the mechanical properties of the surface, which can make players change the way they load and deform the surface. An understanding of this interaction is essential to provide a fair compromise between sport performance, injury prevention and surface durability.

To quantify and describe this interaction some surface and player inputs need to be characterized. From a player biomechanical perspective, sport specific movements should be kinetically and kinematically described. From a surface mechanical perspective, surface physico-chemical and mechanical parameters should be determined. This is recognized to be the key for understanding injury risk to players and wearing damage to surfaces (Stiles et al., 2008).

Most of the current sports surface research has been focused on STPs as they represent more uniform systems which are less influenced by adverse weather conditions, providing year round playing with lower maintenance. However, STPs do not adequately replicate the fundamental playing characteristics for sports, such as cricket, and so NTPs are important to preserve them. Moreover, NTPs represent green spaces in the built environment which are critical for urban ecosystem functioning. In addition, in the UK the majority of outdoor sport is still played on NTPs and they are still preferred by most players, and therefore this supports the fact that further research should not only be carried out on STPs but also on NTPs. Evidence of injury occurrence when playing on NTPs is sparse and usually includes a lack of detail regarding surface characterization, however, some comparative studies between STPs and NTPs suggest a similar injury occurrence highlighting surface traction and impact absorption as the key parameters that may cause injury. Player response to changes in traction and surface cushioning is not well understood, however, and further research is needed into the causal mechanisms that explain injury on both types of surface.

An NTP represents a complex composite material made from a mixture of soil particles, air, water, grass and living micro-organisms that varies in space and time by the action of players and weather conditions. There have been significant changes in the development of NTPs over recent years, particularly at the elite level, using more frictional soil media, to provide for (1) player requirements for faster surfaces with a higher traction component and (2) spectators needs for an attractive environment. Future studies must characterise the nature of NTPs in order to understand how those changes affect their mechanical properties and thus player performance and injury risk.

Loading an NTP soil produces a subsequent deformation or strain that is a function of the interaction of all the parameters comprising an NTP. As a first approximation to this complex problem, mechanical characterization of NTPs can be described in terms of the soil mechanical stress-strain behaviour, which is actually a function of the soil texture, organic matter, soil dry bulk density and water moisture content. The majority of the devices commonly used in sports science to characterize sports surface stress-strain behaviour usually fail to incorporate the complexities of human movement in sport. The general approach of testing NTPs includes devices to measure traction and impact absorption that are portable, easy to operate and inexpensive compared to more powerful equipments in a laboratory environment. The latter provide more precise characterization of the stress-strain behaviour of the surface, essential for understanding both ball-surface and player-surface interactions.

To determine player inputs from sports movements, biomechanical studies are necessary. Unfortunately, to perform biomechanical studies on NTPs is a challenge due to the difficulty with sustaining surfaces in a laboratory environment, which is why such studies are so rare in the literature. Biomechanical research is also limited by ethical considerations as testing player response may be considered reckless if player safety is compromised by injury risk and occurrence. Future research should include an integrated approach using engineering and biomechanical expertise. This will permit greater understanding of how NTPs influence player performance and safety and also how they are affected by player actions. This is considered to hold the key to the future development of more resilient, sustainable, higher performance and safer NTPs for all level of sports.

3. BIOMECHANICAL STUDY

3.1. Introduction

The necessity of quantifying player loading in determining the mechanical parameters of NTPs, and so investigate properly player-surface interactions, was highlighted in Chapter 2. The current chapter details the analysis and characterization of two sport-specific movements, running and turning, performed by a group of players interacting with a range of NTPs in a laboratory environment (Objective 2). First, the selected NTPs are described and characterized in terms of physicochemical and basic mechanical properties (Objective 1). The preparation and maintenance of the NTPs follows. A description of the biomechanical laboratory setup, including the mechanical and biomechanical devices used for kinetic and kinematic data collection is included later in the chapter. Finally, the effect that changes in surface type may have on the player movements will be explored and discussed.

3.2. Materials characterization

3.2.1. Soil material selection

The following three raw materials were selected as test soils for the project:

- A high sand content material (USGA rootzone, supplied by Baileys of Norfolk Ltd., UK) used in the construction of winter NTPs such as modern professional sand construction soccer pitches.
- A clay loam (Ongar Loam, supplied by Binder Loams, Essex, UK) used in the construction of professional cricket pitches and similar to clay based Local Authority winter NTPs.
- A sandy loam (Sandy loam supplied by Baileys of Norfolk Ltd., UK) providing an intermediate sand content condition.

3.2.2. Soil texture and structure

Particle Size Distribution (PSD)

Many of the physicochemical and mechanical properties of soil relate to its mineral skeleton which is defined by the size composition of the mineral soil-forming particles, the soil texture. These particles are commonly separated into sand (2 mm to 0.063 mm diameter), silt (0.063 mm to 0.002 mm diameter) and clay (< 0.002 mm diameter) fractions. Texture classis defined by reference to the triangular classification of the three principal fractions sand, silt and clay defined by the Soil Survey of England and Wales (Hodgson, 1998). The relative proportions of these fractions was determined by sieving and sedimentation using the Pipette Method as per NR-SAS/SOP5/1 based on ISO 11277:1998.

Soil Organic Matter (OM) and mineral content

The soil texture classes distinguished on the triangle of texture make no reference to organic matter content, but no classification of soil texture is complete without some further, qualifying reference to this component (Smith et al., 1996). The percentage organic matter by dry weight in soil was determined by wet oxidation in potassium dichromate as per NR-SAS/SOP4/1 based on BS 1377-3:1990. Soil pH was determined using an electrode pH meter to determine pH in a 1:2.5 slurry with water (Gasser, 1973).

Plant nutrient analysis

Plant available Phosphorus, Potassium and Magnesium was determined to ensure that these nutrients were not limiting to turf growth. In addition the pH was determined to ensure that this was not limiting to plant growth. Available phosphorus was determined spectrophotometrically using Olsen's extraction for plant available phosphorus in sodium hydrogen carbonate as per NR-SAS/SOP15/1 based on ISO 11263:1994. Plant available potassium and magnesium were extracted in ammonium nitrate and determined by atomic adsorption flame photometry (Appendix A).

Dry bulk density (ρ_b) and moisture content (θ)

The way in which soil particles are organized and held together is termed the soil structure and it is as important as soil texture in regulating the movement of air and water in the soil, both of which impact greatly on the soils physicochemical and mechanical properties. The soils in this experiment were unstructured, however, and their arrangement of packing is described by the determination of dry bulk density (ρ_b):

$$\rho_b = \frac{M_s}{V_t} \qquad \text{(Equation 3.1)}$$

Where M_s is the dry mass of soil in the volume V_t. A compacted soil will have a greater density and lower porosity than a less compacted soil of the same texture (Scott, 2000). The density is not cross comparable between different textures as it depends on the pore and particle size distributions and the differences in density among soil forming minerals.

The soil water content is influenced by the soil structure (Brady and Weil, 2002). The extent to which water will either accumulate on the surface of the soil, or infiltrate, will depend on the moisture content of the soil and the nature of the soil's pore system. Water Holding Capacity (WHC) is a function of pore size distribution which in turn is a function of PSD and this again of soil density. Water will either drain freely or be retained at high tension in a soil dominated by large or small pores, respectively. Greater WHC is achieved with a well graded soil that has more pore space than a poorly granulated or compacted soil (Bullock et al., 1985). Soil water release characteristics were determined using a combination of sand tables and pressure membrane equipment as per NR-SAS/SOP30/1.

If the soil is compacted by mechanical means, the soil particles are made to pack more closely together and the dry bulk density of the soil increases. At an optimum moisture content, the water acts as a lubricant and allows the soil particles to squeeze together more easily. Too little water content will not allow soil particles to move freely against each others resulting in a smaller dry bulk density. Too much water content will also cause a smaller dry bulk density as a consequence of an excess of incompressible water between soil particles. For a given compaction energy, there is an optimum water content that will obtain a maximum dry density (Brady and Weil, 2002). Optimum moisture contents were determined using a standard 2.5 kg hammer Proctor test (BS 1377: Part 4:1990).

Water content is presented as volumetric moisture content (θ_v) or gravimetric moisture content (θ_m) as a percentage:

$$\theta_v = \frac{V_w}{V_t} \qquad \text{(Equation 3.2)}$$

$$\theta_m = \frac{M_w}{M_s} \qquad \text{(Equation 3.3)}$$

$$\theta_v = \theta_m \rho_b \qquad \text{(Equation 3.4)}$$

Where M_w and V_w are the mass and volume of water, respectively; M_s is the dry mass of soil in the volume V_t and ρ_b is the dry bulk density.

3.3. Experimental methods

3.3.1. Soil and turf preparation

Portable pitch system

The NTPs were prepared at Cranfield University and tested in the sports biomechanics laboratory at the University of Exeter. This was a challenge in that the laboratory is indoors due to the requirements of the infra-red motion capture system used to study player movement and not conducive to sustained turf culture. To overcome the problem, the surfaces were installed using a ‘portable pitch system’. Polypropylene containers (600 x 400 x 50 mm) were selected as a portable surface system (supplied by LINPAC Allibert, UK). These trays were relatively cheap, light, and easy to handle and transport compared to other containers made of steel or wood. The 600 x 400 size was selected because this was the size of the force plate that was used for the biomechanical tests. Holes were drilled into the bottom of the trays to allow the drainage of water. The 50 mm depth of the tray was adequate to obtain the minimum rooting depth and therefore stability properties to simulate NTPs found outdoors. Another advantage of the depth was that mass was limited to suitable manual handling limits and by limiting mass the inertia of the force plate tray was also limited, increasing sensitivity of force measurement. This solution has some disadvantages: there was a risk of insufficient depth for root development for the grass plant compared to an outdoor sports field. Secondly they had rigid edges that could have affected the biomechanics of players if a player was to contact a ridge when running.

The total number of trays constructed was 138. This comprised 54 test trays placed on the force plate (3 conditions x 2 movements x 9 players) and 84 other trays used to create a 'runway' prior and posterior to the force plate condition.

Soil compaction

The trays were filled in three batches of one of each of the test soil materials and hand rolled to obtain the maximum density that the process allowed by manual compaction. Because of concerns about damaging the plastic trays, a mechanical press could not be used.

Table 3.1 Dry bulk densities achieved after hand rolling compaction.

Variable	Sand	Clay Loam	Sandy Loam
ρ_b (g cm^{-3})	1.75	1.30	1.50

The densities achieved for the soils by hand rolling shown in Table 3.1 were considered to combine a reasonable structural strength with acceptable water percolation properties for each soil type.

Turf selection

In general terms, an NTP could be viewed as a soil base with a turfgrass layer on top. In reality, the turf is a unit of soil with a mixture of selected grass varieties growing in it; with a root structure within the soil matrix. The composition of the turfgrass species varies dependent on the sport involved and the level of use that an NTP receives. In this project, LT6 Sportsturf (Lindum Seeded Turf Ltd, UK) was used. This is a turf specifically developed for winter sports pitches such as football and rugby and comprises a mix of Perennial Ryegrass (*Lolium perenne*), Red Fescue (*Festuca sp*) and Meadow Grass (*Poa sp*). The mixture of perennial ryegrasses and fescue incorporated in the seed-mix provides good wearing resistance whereas the meadow grass provides good self-repair recovery properties.

Figure 3.1 A roll of the washed turf purchased for the project.

The turf was supplied washed and rolled (Figure 3.1) by the turf producer and transplanted at Cranfield. Washed turf was used, rather than seed because of the need to have a usable surface in a short period of time when temperatures were too low for grass to germinate.

Turf installation and care

The turf is a mass of living plants and a certain amount of care and maintenance was required to ensure it grows to its full potential. A fertiliser (Turf Line, 10-6-4 NPK) was applied and raked into the soil before the turf was installed, following the manufacturer's application rates of 35 g m^{-2}.

To transplant the turf, the soils were moistened and their external surface was slightly raked over to produce a smooth, firm but not compact surface to ensure good establishment of the turf. Immediately after the turf was delivered to Cranfield and to avoid putting un-necessary stress on the plant, the turf was laid on the trays and the trays were placed in the open air and left living outside from the 3rd of April to the 29th of May 2006. Strips of turf were laid over and shaped to fit sets of 4 plastic trays containing the soil. Full contact between the turf and the soil was ensured by pushing with a small hand roller. The edges and ends were pushed against each other and a sharp half-moon spade was used to cut the end of a row without stretching the turf. The turf was allowed to grow over the ends of trays to remove the effects of shrinkage and to prevent a player from adjusting their movements in preparation for contact with a different surface (as will be discussed further in Section 3.3.2). To keep digging mammals and birds off the laid turf a protective surrounding fence and a scarecrow were installed by the turf.

Figure 3.2 A view of the trays (600 x 400 mm) before (left) and after (right) turf laying.

Watering

The newly laid turf was watered plentifully within half-an-hour of installation. Until the turf was definitely established several weeks after, the soil below the turf was maintained sufficiently moist to enable the grass plant to survive and to grow a root system. Water was applied according to weather conditions that dictated the frequency of irrigation required without causing prolonged saturation of the soil as standing water limits grass growth due to low oxygen levels around the roots. The turf was kept moist but not completely saturated and it was immediately watered when any signs of the turf drying out were observed.

Daily top-up waterings required lesser amounts to be applied but this depended on levels of ET rate due to temperature and wind conditions (Fry and Huang, 2004). Thus, when heavy rainfalls occurred during the establishment phase then some reduction in the water applied was made. On the contrary, when short showers took place sufficient water was externally applied. Watering was usually applied when the air temperature was cooler, that is to say, early in the morning or late in the evening to minimize ET.

Mowing

The grass was periodically checked by lifting up a corner of turf to see if the roots had grown into the soil and it was first mowed once it was well rooted (approximately after 4 weeks). At the initial stage, when the turf was more sensitive to the wear of a normal mower, this task was carried out using hand shears with sharp blades to prevent from tearing up turf by pulling out the grass by its roots. Clippings were removed to minimize thatch, the layer of decomposing grassy material located between the grass blades and the soil.

The more it is mowed, the more individual grass leaves will grow and therefore the turf will have a denser sward. Letting the grass get too long leads to weak growth, which in turn invites attack by fungal diseases and allows weeds to establish (Adams and Gibbs, 1994). Once the turf received the first cut, the old adage - a little and often - was applied to grass mowing and the height of cut was kept at 35 mm (between weeks 4 and 6).

When the roots had completely established into the soil beneath (from week 6 on), the mowing height was then safely lowered to around 25 mm, at a frequency that ensured that the length of turf removed was never more than one third of the grass length at one time. A sharp bladed rotary Flymo mower was used at this final stage of the turf preparation, which was found to increase the grass height homogeneity and decrease the time consumed for the operation compared to using hand shears.

Weed control

Due to the natural weed seed dispersion, it was inevitable to find occasional undesired grass and weed species establishing themselves. These were eradicated by removing them by hand as they appeared.

Maintenance fertilizer applications

Once the grass plants had rooted into the soil they took on an appearance and growth habit dictated by the soil. Due to the limited nutrient source of the tray system (in particular the sand rootzone and sandy loam treatments), the nutrient content was enhanced artificially to sustain proper turf growing. Feeding was repeated on the 24th of April and on the 15 of May 2006 during the growing period using a liquid fertilizer (ProTurf SEAMAC, 6 % Fe + 3.4 % SO_3 + 2.5 % N + 2 % MgO) was applied at 1.75 L / 500 mm^2 in 10 - 20 L of water, following the manufacturer's instructions.

Transport of the surfaces from Cranfield to Exeter

Three wooden racking systems (Figure 3.3) were specially designed and manufactured to accommodate the trays and allow transporting the surfaces from Cranfield University at Silsoe to the University of Exeter by road. The tray rack system was handled using a pallet truck and a tail lift on a 7.5 t lorry.

Figure 3.3 The shelves system for trays transporting containing some of the turfed trays inside.

3.3.2. Experimental set-up

Players and shoes

It is known that not every subject will perform a movement in the same manner (Nigg et al., 1986b). It may therefore be necessary, depending on the intended application of the research results of future studies to minimise player (subject) variability by selecting participants from a similar level of task or sporting ability. However, if one purpose of the research is to generalise results to a wider population selecting non-homogenous group of subjects with a range of abilities to assess conditions may be more applicable (Vincent, 1995; Bryman and Cramer, 1997). In the present study, 9 male volunteers with ages comprised between 18 and 25, who had not been injured for the last 6 months and with various grades of experience of football or rugby were recruited from a university or club standard. They all regularly participated in training and match playing sessions on NTPs. The mean player mass was 79.9 ± 2.7 kg (mean ± standard error). Approval for the collection of data from human participants was obtained from the School of Sport and Health Sciences, University of Exeter Ethics Committee. Informed consent was obtained prior to testing and players were made aware that they could withdraw from the testing procedure at any time.

Players were assigned standard metal studded soccer boots (Nike Air zoom Total 90, Figure 3.4) in their size (Size 10, 11, 12 UK).

Figure 3.4 Nike Air zoom Total 90 used in the experiments.

Sports specific movements

Analysis and observation of any sport reveals movements that are frequently repeated and thereby characterize the sport (Dixon and Stiles, 2003). Running is one of the movements usually involved in traditional sports and so in relation to the assessment of NTPs, studies of running are invaluable foundations on which to formulate future research in specific sports on NTPs.

In relation to sport-specific movements in addition to running, there is less published biomechanical research. A pilot study carried out by Stiles et al. (2006) undertook an initial biomechanical characterisation of three sports specific movements (running, turning and accelerating from rest) performed in the laboratory by two players. The experiment successfully showed how natural soil media can be incorporated into a laboratory and used as a surface on which sports specific movements can be performed and human response analysed. Changes in surface cushioning properties were detected, as shown by differences in peak forces and peak rates of loading between different movements for a fixed sand rootzone condition turfed with ryegrass as the one used for the current study. The purpose of the present research is to assess the effect of NTPs, on three different soils, with a group of players performing two typical sports movements: running and turning. For the turning movement the inside turn technique was required from the players. In this technique, at the time of turning, the foot is already turned when it steps on the force plate, preventing the runner from turning it on the ground which could cause them an injury. Figure 3.5 shows how the two movements were performed in the laboratory.

Figure 3.5 Laboratory set-up. Players performing running (top) and turning (bottom) movements in the biomechanics laboratory. Players step on the corresponding run-up trays and force plate tray (longitudinally placed to cover the force platform) and then continue on the corresponding run-off trays for each of the conditions. Infra-red motion cameras can be seen on both walls. White reflective markers are attached on the right leg of the players.

Laboratory layout

Trays were laterally positioned cross-ways in the biomechanics laboratory at the University of Exeter, over a non-slip matting (6 mm thick) to form a continuous 10 m runway. One tray was longitudinally placed to cover the force platform. Based on the pilot experiment an optimum 6 m runway length prior the force plate (run-up) was produced to provide enough distance to meet the force plate naturally and to gain sufficient running speed to perform the movement within the confines of the laboratory. Similarly, an optimum 4 m distance after the force plate (run-off) was produced to allow players to stop naturally and safely. A surrounding supportive runway of rubber matting and foam covered with an acrylic top-surface was constructed on either side of the turf runway for the safety of participants. A schematic picture of the laboratory layouts is illustrated in Figure 3.6.

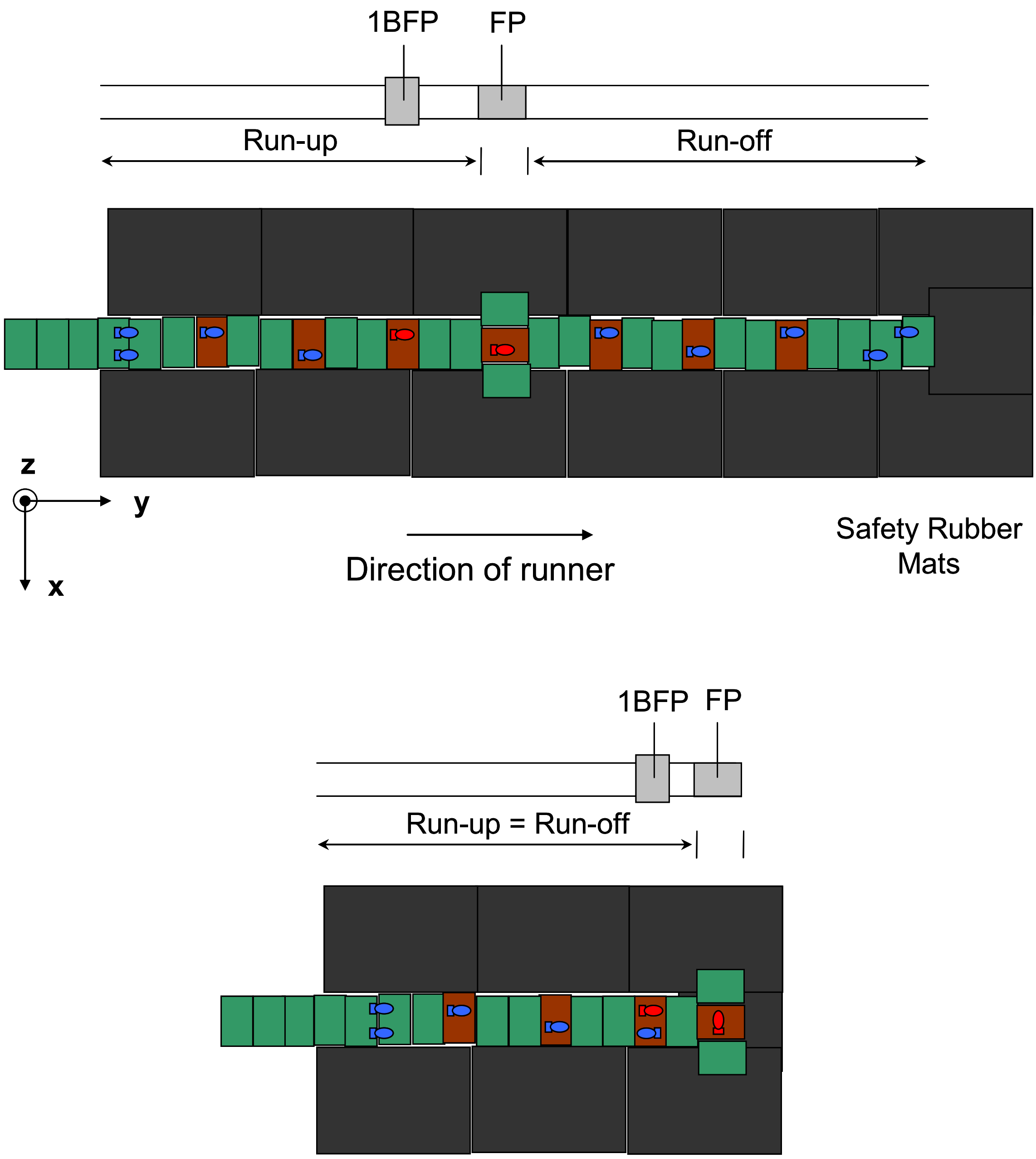


Figure 3.6 Laboratory layout with the runway (green + brown) and steps followed by players for running (top) and turning (bottom). The consistency for each condition of the force plate tray (FP) and the tray before the force plate (1BFP) is critical to avoid undesirable adaptations in movement performance. For turning, the run-up is also the run-off. Surrounding safety rubber mats shown in black. Blue footprints = run up + run off. Red footprints = critical steps. Axes convention used throughout shown for x, y, z.

Starting with the pilot experiment, player footsteps were studied and the laboratory tray layout designed accordingly to produce an improved runway. Runners left a gap of two trays between consecutive steps and it was agreed to lie the three different conditions alternated along a single runaway ensuring that the runners were only using the corresponding ones for each condition at all times. This implied less tray movement and lifting between condition tests in the lab as well as a reduction in the number of trays needed inside the lab which minimize the time to be waited by the subjects compared to, for instance, having the three different conditions laid down on the laboratory floor at the same time.

A slightly different layout was used to perform the second movement involving turning 180 degrees, where the previous run-off was eliminated with the players exiting the force plate pointing in the direction from which they had started the run-up. The force plate was directly supported by the rubber mats.

Laboratory set-up

As previously stated in Chapter 2, the human system is complex with the availability of multiple degrees of freedom and as such, variability. This effect of intra-player variability on reliability can be accommodated through the collection of multiple measurements (Bates, 1996). It appears that rules are not yet rigidly established for the total trial collection size to yield data that is representative of a group's movement behaviour while performing a given task. Bates et al. (1992), after carrying out tests related to statistical power and sample size, based on vertical ground reaction force data, concluded that the number of trials required to fulfil the measures of trial stability and satisfy statistical power for 5, 10 and 20 players was 10, 5 and 3 trials respectively. The majority of biomechanical running studies however, concentrate on data collections of between 8-10 trials per subject. With this information, in this research study 10 successful trials by each subject were required for each condition. Analysis of data in the pilot study allowed the number of trials required in order to satisfy trial stability to be confirmed prior to the main data collection phase of the study.

Players were informed of the desired movement through demonstration by researchers in the laboratory but they were not provided with any specific information regarding the differences between the surfaces. Players were required to make a right-footed contact with the target force platform tray during each trial without adjusting their running stride and rhythm.

Due to the size of the force plate (600 x 400 mm) it was only possible to collect data for one running step. Sometimes, players tend to alter their natural running style to land on the right tray with the right foot. For this reason, players were requested to perform familiarisation trials for each movement prior to the start of data collection until they were confident with executing the movements and location of the desired foot landing on the force plate had been repeatedly achieved (Bates et al., 1983). During practice running trials, starting positions were marked out in the laboratory to assist players in making contact with the force plate tray using their natural running style during their fourth stride on the runway and without adjusting their running stride.

A constant running speed of 3.83 m s^{-1} ($\pm$ 5 %) was required between two sets of photocell timing gates set 1 m away from the centre line of the target tray (2 m distance between photocell sets). Where players failed to make contact with the force plate, dramatically altered their entry speed or failed to perform a typical movement trial, data were discarded, verbal feedback was provided by the researchers to try and correct the fault and the trial was repeated. A measure of the speed of a movement was used to indicate an initial level of trial reliability. For each change in surface, the subject performed at least a further 3 familiarisation sequences prior to collection of data whilst a spare tray of turf was positioned in the target area of the runway. Then, 10 trials on each surface were performed for each specific movement.

It is critical for the biomechanical experiments to ensure that players performed their movements without interruption from variation in surface properties prior to the force plate that would cause undesirable adaptations to occur in movement performance. Special attention was therefore focused on the force plate tray (FP) itself and the tray of the same condition step right before the force plate (1BFP) in order to make sure that the mechanical properties of those trays were kept as consistent as possible for every condition. Ideally, trays should be changed every time that a player runs over it. Due to financial and time constraints however it was agreed that only the target FP tray would be removed and preserved for post-hoc analysis after each subject had completed 10 trials on the one soil condition. Each target tray was therefore unique to a subject and had 10 trials of data on it. If not seriously damaged, all other trays were kept for future test sessions in order to create another runway for another subject on another day for one of the three conditions. All trays were relocated outside the lab overnight, supplied with water and left to recover for one or two days depending on laboratory test requirements and obvious turfgrass damage. Trays were maintained at reasonable volumetric moisture levels to ensure the survival of the grass (30 % sand, 35 % clay loam and between 30-35 % sandy loam).

Players were required to visit the laboratory on one occasion to complete running trials on all three test surfaces executing a total of 30 successful trials per session. Data for turning were collected on another day to minimise the influence of fatigue on the task outcome.

3.3.3. Biomechanical testing

Kinetic data: force and pressure analysis

An AMTI force plate (Advanced Mechanical Technology Inc, Massachusetts, USA) situated flush within the concrete floor below the tray runway collected force data in the 3 principal Cartesian axes (x medial-lateral, y anterior-posterior and z vertical) at a sampling rate of 960 Hz. A threshold of 10 N magnitude was breached (F_z > 10 N: initial contact, F_z < 10 N: foot-off) and this point was used to define ground contact. Ground reaction force (GRF) time-histories for each movement were compiled.

An RSScan (Belgium) pressure insole system sampling at 500 Hz was inserted into the shoes of the player and used to assess the foot pressure distribution during a footstep. The collection of pressure data was continuous throughout an 8-second trial which was triggered by the researchers. Extraction of individual steps in sequence was done manually in the proprietary FootScan Insole software supplied with the insole system (version v.2.34, 2006) based on the ground contact time indicated by the force plate data. The closest step to the ground reaction force contact time was selected. The foot plant was split into two anatomic regions corresponding to the rear-foot and fore-foot as shown in Figure 3.7 and the pressure evolution for each mask was monitored and analyzed in MATLAB 7.2 (R2006a, MathWorks, USA). Despite data for both feet being collected for all the trays, data analysis was focused on the right-foot step occurring over the force plate.

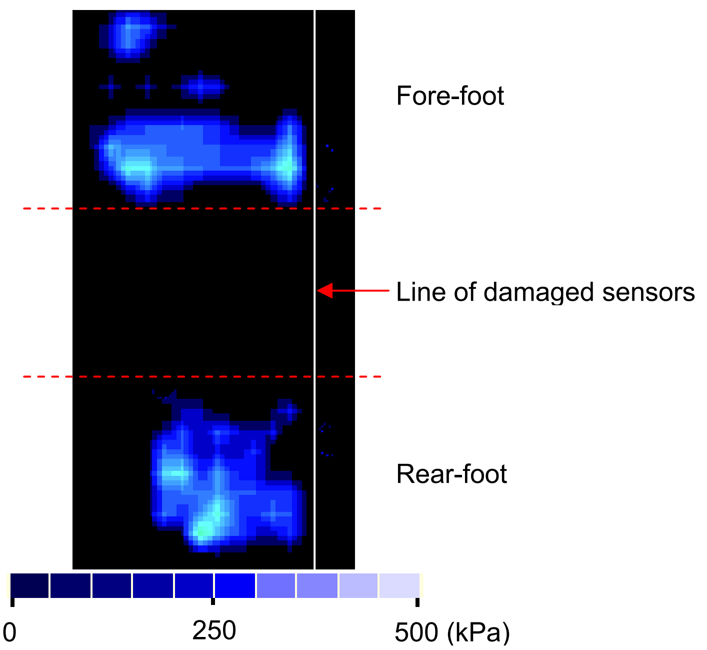


Figure 3.7 Typical pressure distribution for the right foot showing rear-foot (foot's bottom third) and fore-foot (foot's upper third) masks created for kinetic analysis. White line on the right hand side represent a hypothetical 'blank line' of damaged sensor recording no data.

The kinetic data from the pressure insoles were exported into MATLAB for further manipulation and analysis. Any force transducer 'blank lines' (Figure 3.7) within the insole system were identified and taken out in post-hoc analysis so that all the players had the same number of active sensors. Raw force data were smoothed using a 9th degree polynomial spline and then contact area time histories for the entire foot and the two sub-regions (rear-foot and fore-foot) were produced (Hennig, 2002). This was calculated by adding up the number of activated sensors at every frame and multiplying the count by the area of a single sensor (25 mm^2). Finally, pressure time histories were calculated by dividing the force output by the previously calculated contact area at the corresponding frame in time (see the MATLAB flow diagram in Appendix B).

The following kinetic variables were recorded and used to characterize the movements and also to determine whether player biomechanical adjustment to changes in surface could be detected.

From the force plate:

- Peak vertical (F_z^{max}) and horizontal force (F_y^{max}) and times of occurrence
- Peak vertical (dF_z^{max}) and horizontal anterior-posterior (dF_y^{max}) rate-of-loading and times of occurrence
- Peak ratio $(F_y \ / \ F_z)^{max}$ between horizontal and vertical force during braking phase and times of occurrence

The medial-lateral force component (F_x) was measured but was not included in the analysis. This component was observed to yield negligible magnitudes compared to F_z and F_y in the pilot experiment (Stiles et al., 2006) and in terms of injury/performance there is a limited rationale to support monitoring it (Stiles, pers. comm., 2008).

From the insole devices:

- Peak (A^{max}) and mean ($\bar{A}$) foot contact area
- Peak foot (P^{max}), rear-foot (P_R^{max}) and fore-foot (P_F^{max}) pressure and times of occurrence
- Peak foot (dP^{max}), rear-foot (dP_R^{max}) and fore-foot (dP_F^{max}) pressure rate-of-loading and the times of occurrence

The force and pressure loading rates (dV) were calculated according to Miller (1990) using the first central difference method as described in mechanical terms in the Equation 5.

$$dV = \frac{(V_{final} - V_{initial})}{(t_{final} - t_{initial})} \qquad \text{(Equation 3.5)}$$

Where, V_{final} is the final force or pressure magnitude (the data point immediately following the point at which loading rate is to be calculated), $V_{initial}$ is the initial force or pressure magnitude (the data point immediately prior to the point at which loading rate is to be calculated) and t_{final} and $t_{initial}$ are the time components of the respective final and initial data points. The loading rate characterizes the initial part of the force and pressure time-history, especially since for some subjects, particularly mid-foot strikers during running, there is absence of an initial peak passive force (Cavanagh and Lafortune, 1980; Miller, 1990). All force, pressure and loading rate magnitudes were normalised to body weight (BW).

Kinematic data: motion analysis

A Peak Motus Real Time 8 camera set up (automatic, opto-electronic system; Peak Performance Technologies Inc, Englewood, Colorado) was used to assess the motion characteristics of the lower extremity (120 Hz). The cameras were calibrated, arranged following a standard procedure and remained in their positions throughout the whole data collection process. The position of the cameras was partially shown in Figure 3.5 as the red LEDs shining on both walls. A combined and adapted version of the joint co-ordinate system presented by Vaughan et al. (1992) was employed to monitor joint movement at the ankle and knee. Joint angles were referenced to a relaxed standing position. Nine reflective spherical markers were located at anatomical points to define joint centres (hip, knee and ankle) and segments of the leg (thigh, shank and foot). For both movements, markers were placed on the right lower extremity and again a right-footed step was analysed for both the running and turning movements. The marker convention and location is displayed in Figure 3.8. This analysis was performed by Dr Vicky Stiles and Dr Sharon Dixon of the Exeter Biomechanics Research Team, School of Sport and Health Sciences, University of Exeter, Exeter, UK.

Two dimensional analysis of the lower extremity was undertaken. A hierarchical clustering technique was performed on the kinetic and kinematic data and different player behaviours were defined. Mean values and standard errors for the different groups that the cluster analysis assigned for each of the above mentioned variables were calculated using group player mean data. Group means were compared using general linear models and analysis of variance using ‘condition x group’ interaction with repeated measures to determine whether statistically significant differences existed between surfaces and groups ($p < 0.05$). Analysis was conducted in the statistical language R (v 2.4, 2006)

In addition to the above listed kinetic (force and pressure) variables, player adjustments to changes in surface condition were monitored using the following kinematic variables during the stance phase:

- Initial foot (φ^i), ankle (α^i) and knee (κ^i) joint angles
- Peak ankle (α^{max}) and knee (κ^{max}) joint angles, range of movements (ROM) and times of occurrence
- Peak foot ($d\varphi^{max}$), ankle ($d\alpha^{max}$) and knee ($d\kappa^{max}$) angular velocities and time of occurrence

- Initial vertical heel impact velocity (dh_z^i)

Initial kinematics were taken at the frame immediately prior to ground contact by synchronized collection of force plate data.

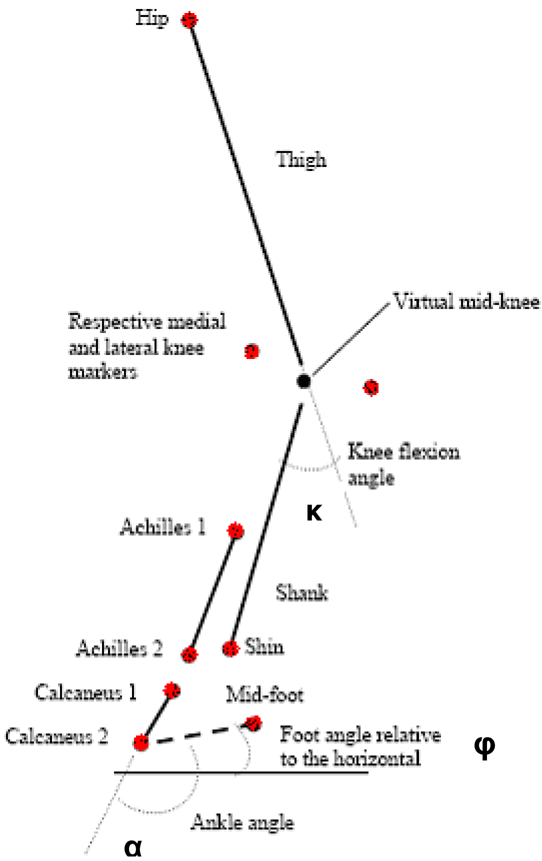


Figure 3.8 Marker conventions used to construct the joint coordinate system of the lower limb. This joint co-ordinate system required the following marker placements: hip, lateral knee, medial knee, Achilles (1 and 2), shin, calcaneus (1 and 2) and mid-foot.

3.3.4. Mechanical testing

The surface volumetric moisture content (θ_v) was measured in situ immediately before player testing using a theta probe. The device (Figure 3.9) works by inserting it into the surface and then by sensing the apparent dielectric constant of the soil, the moisture is worked out (Gaskin and Miller, 1996).

The surface hardness (in gravities, G) was measured using a calibrated CIH (Figure 3.9; Appendix C) as per BS EN 12231:2003. The device works by manually dropping a flat-ended cylindrical mass (0.5 kg) with an accelerometer from a known height (0.55 m) over the surface 3 times and measuring the peak deceleration on the last drop.

The shear strength (in kPa) was measured using a shear vane (Figure 3.9) as per BS EN 14954:2005. The device works by inserting the vane (33 mm length x 16.5 mm width) into the surface and then the torsion force required to cause shearing is calculated by rotating the torque meter built into the vane head.

Measurements of moisture content and hardness were taken from two randomly selected trays on every runway built and in every 10 trials from the FP and the 1BFP to check that the runway was mechanically consistent. Shear strength was only measured on the force plate trays as being a semi-destructive method, it was not possible to continually make holes in the turf that was going to be reused for another runway as this could have been dangerous for the athletes. Differences within conditions and between conditions were determined using ANOVA ($p < 0.05$).

Figure 3.9 Soil test equipment used.
Left to right: Theta probe, Clegg Impact Hammer and shear vane.

Soil deformation was measured from the footprints that players left on the force plate trays. Three force plate trays were selected per movement and condition for the following analysis. Firstly, the grass was mowed as short as possible. Then, footprint shape was manually recorded using a mechanical profile meter along the 2 orthogonal horizontal axes in relation to the container limits, that is, lengthwise and transversally. Transverse measurements where taken on the rear-foot and fore-foot (heel and ball of the foot areas, respectively). A digital camera Fujifilm Finepix 6900Z was used to digitize the profiles measured. An image analysis subroutine was developed in MATLAB to account for the area of the soil deformation profiles (see the MATLAB flow diagram in Appendix B).

3.4. Results and discussion

3.4.1. Soil characterization

The soils selected for the project are made up of a mixture of particle size grades that indicates different textural classes as shown in the Table 3.2. A cumulative grading curve (Figure 3.10) and a textural triangle (Figure 3.11) are included to assist interpretation and to aid comparisons between conditions.

Table 3.2 Particle Size Distribution (PSD) and Organic Matter (OM) for the three soil conditions.

Particle (%)	Size (mm)	Sand	Clay Loam	Sandy Loam
Sand	2 - 0.063	98	29	58
Silt	0.063 - 0.002	1	45	29
Clay	< 0.002	1	26	13
OM (%)	-	1	3	2

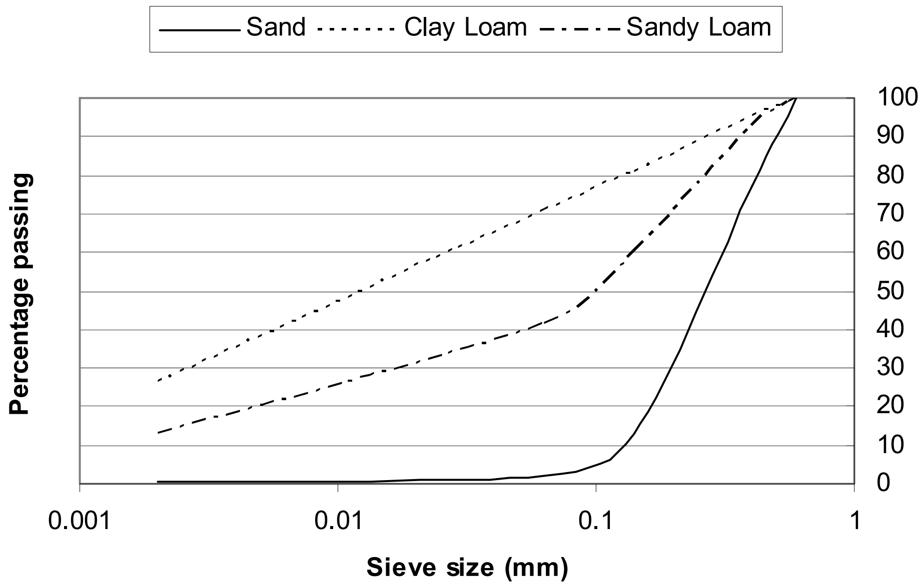


Figure 3.10 Cumulative grading curves for the three different soil textures.

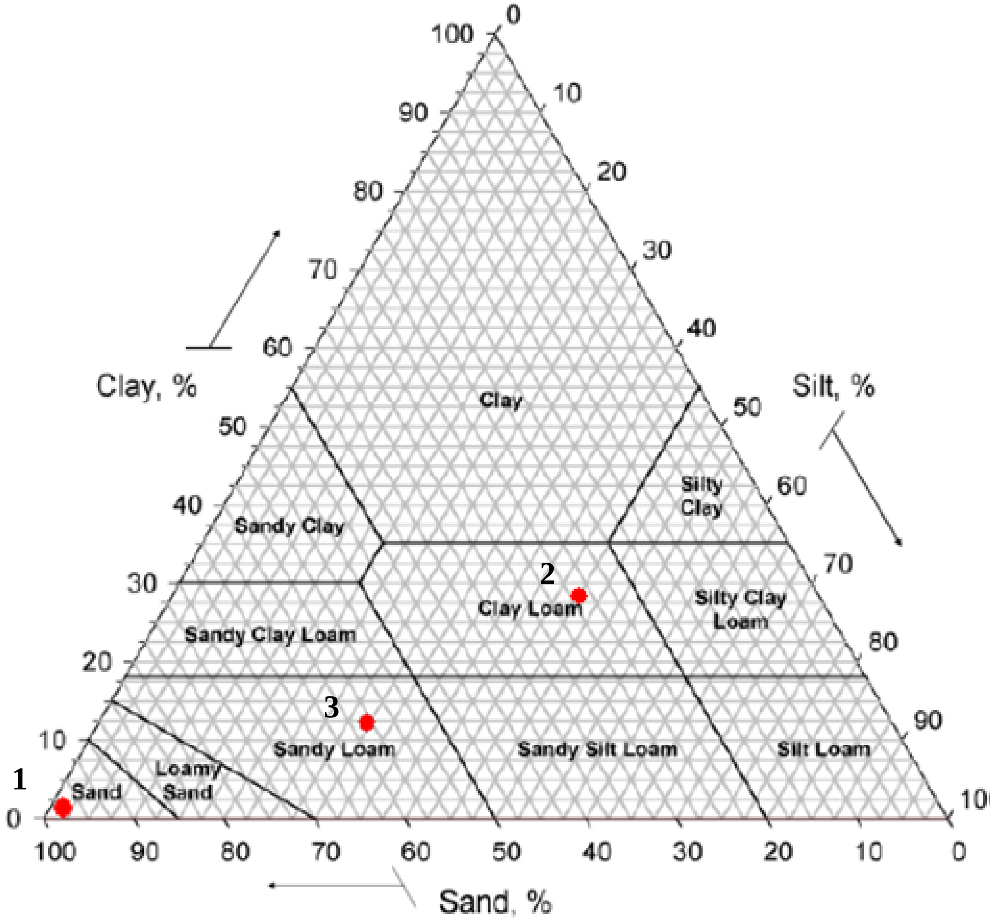


Figure 3.11 Textural triangle (derived from Hodgson, 1997) showing the PSD for the soils involved in the research: Sand (1), Clay (2) and Loam (3).

In the textural analysis, the conditions were classed as 'Sand' (with a high proportion of sand size fraction), 'Clay Loam' (with a high proportion of clay size fraction) and 'Sandy Loam' (with an intermediate proportion of sand and clay particles), respectively. The Clay Loam is dominated by fine particles and small pores that result in a higher relative moisture content at a given matric potential. The Sand is characterised by large particles and large interconnected pores that drain rapidly as matric potential increases, that is, as the soil dries out. This is illustrated in the steeper slope from the curvature of water release characteristics measured in (Figure 3.12). In general, as relative saturation decreases, the water retained within the soil is held increasingly tightly and the strength of the soil increases. This is the fundamental basis for the concept of 'effective stress' in soil of Terzaghi (1943) and will be explained in Chapter 4.

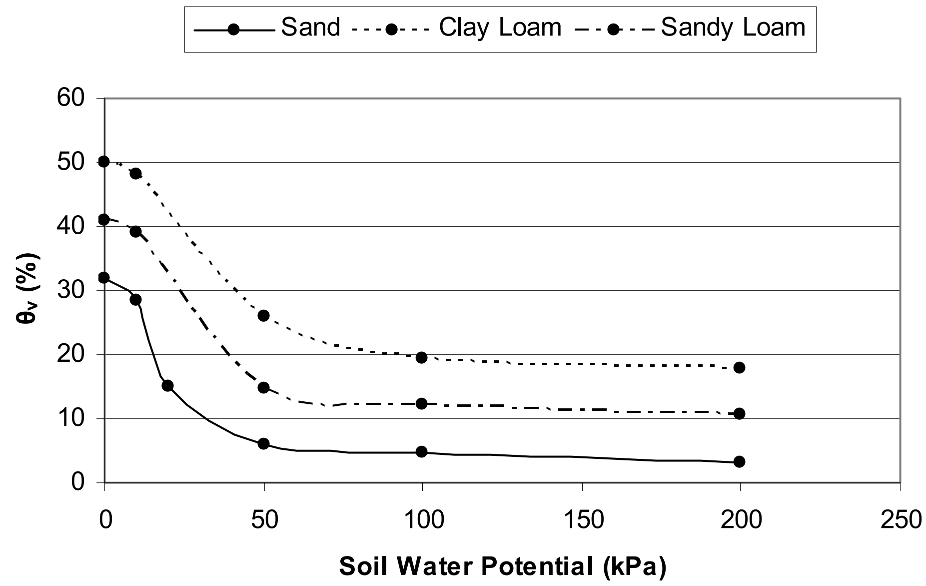


Figure 3.12 Relationship between volumetric moisture content (VMC) and soil water potential for the three different soil textures.

The different textural classes have varying characteristics in the context of this study. Soil texture has a large influence on water retention. Texture also affects the mechanical properties of the surface which at the same time is also influenced by the water content. The high sand content present in the Sand condition indicates an open microstructure of larger pore diameters between particles that will allow free water drainage (high hydraulic conductivity). However, unless fortified with organic matter, this soil presents a low nutrient retention for the grass plant. This is due to the far lower ability of sandy textured soils to absorb cations (i.e. its cation exchange capacity, CEC) than for clay textured soils. This is supported by the soil chemical analysis performed that reported a short nutrient supply for the Sand condition (see Appendix A). The necessity for higher relative moisture content (closer to saturation) found for the Sand condition compared to the other two can be understood by the lack of internal cohesion between sand particles as a result from their inert mineralogy. This implies a relatively greater amount of water is needed to improve the water tension between the pores of the soil holding the particles together and to provide sufficient soil strength to sustain the experiments on this condition. However, there is a limit to this as too much water will bring particles apart so decreasing soil strength.

The Clay Loam condition readily holds more water because of the size of the pores and also due to a high content of clay particles that carry a charge which also enables them to store plant nutrients. Clay particles have an electrostatic charge derived from net substitutions in the mineral structure. Generally speaking, clay minerals are alumino silicates composed of sheets of interlocking silica (tetrahedral) that alternate with sheets of aluminium oxide (octahedral). The silica layers consist of a series of silicon and oxygen atoms, in the ratio of 1:4, forming small pyramid-shaped structures called silica tetrahedra. When these consist of pure silicon and oxygen they form the mineral quartz (most of the sand grains found in soils are composed of quartz). Sometimes atoms that are similar in size to silicon combine with oxygen to form part of the silica sheet. Although similar in size, their chemistry is different from that of silicon. Substitution into the octahedral sheets for Al that is more common, however. This fact often causes a charge imbalance, which results in a permanent negative charge.

Depending on the clay mineral type, water can be allowed to penetrate between adjacent clay minerals hydrating substituted cations (such as Mg^{2+} and Ca^{2+}, allowing them to swell and shrink depending on the water content. This charge creates an inter-particle binding strength with small pore size distributions leading to a low hydraulic conductivity. Thus, a steady release of water as the soil dries can be expected from the Clay Loam compared to the rapid switch that occurs for the Sand condition, as was determined in the water released curves obtained. A lot of this water will be held in very small pores (particularly if compacted) so the plant will not necessarily be able to access it. The Clay Loam condition was seen to be the most sensitive to changes in moisture, exhibiting swelling and shrinking in response to wetting and drying altering the mechanical properties, which decreased with increasing water content because the bonds that hold the particles together in structural units due to Van der Waals forces (attraction between oppositely charged surfaces and organic matter) are weakened as more water is absorbed.

The results obtained from the Proctor test on the Sand and Clay soils showed that starting from a dry condition, the attainable dry bulk density at first, increases with increasing soil wetness, then reaches a peak of maximum density at optimum moisture (Table 3.3, Figure 3.13). Beyond this point, the density decreases again to a point where the soil is fully saturated. The Sand reached saturation at around 15% (θ_m) presenting a bulk density close to the maximum density achievable by compaction whereas the Clay reached saturation at around 25% (θ_m) at much lower bulk density.

The Sandy Loam presents an intermediate size of particles The wide range of particles sizes present in the Loam suggests an intermediate texture and so an intermediate behaviour in terms of water and nutrient retention capacity. A sign of this is the moderate water release gradient which that retains a median amount of water compared to Sand and Clay Loam.

Table 3.3 Optimum dry bulk density (ρ_b) and gravimetric moisture content (θ_m) from a Proctor test.

Variable	Sand	Clay Loam
ρ_b (g cm^{-3})	1.80	1.80
θ_m (%)	11.50	15.00

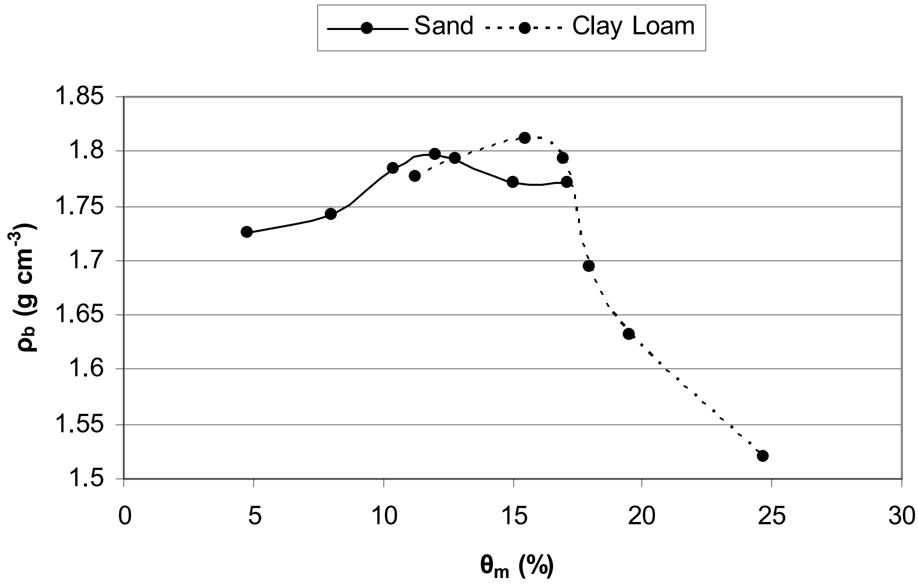


Figure 3.13 Relationship between dry bulk density (ρ_b) and gravimetric moisture content (θ_m) following compaction during a Proctor test.

3.4.2. Mechanical data

The results from the ANOVA ($p < 0.05$) performed on the moisture content, hardness and shear strength measurements taken for each movement and surface are presented in Table 3.4.

Table 3.4 Group mean and standard error data for 9 players running (RN) and turning (TN).

Variables	Sand	Clay Loam	Sandy Loam
Running			
θ_v (%)	30.29 ± 0.68	30.10 ± 1.89	30.83 ± 0.72
% Saturation	81.78	61.66	71.13
Initial Hardness (G)	58.56 ± 1.81	60.64 ± 3.58	61.22 ± 1.92
Final Hardness (G)*	63.12 ± 2.73	71.21 ± 4.98	65.47 ± 2.91
Initial Shear (kN m^{-2})	21.74 ± 1.26	24.56 ± 1.57	24.09 ± 1.07
Final Shear (kN m^{-2})	23.32 ± 1.23	25.79 ± 1.64	24.79 ± 1.24
Turning			
θ_v (%)	30.12 ± 0.73	29.51 ± 1.67	30.31 ± 0.87
% Saturation	81.27	60.26	69.76
Initial Hardness (G)	57.85 ± 2.93	61.81 ± 3.18	60.11 ± 3.01
Final Hardness (G)	53.12 ± 5.93	63.24 ± 6.98	59.12 ± 6.02
Initial Shear (kN m^{-2})	20.94 ± 1.19	24.56 ± 1.57	22.56 ± 1.57
Final Shear (kN m^{-2})	23.61 ± 1.71	22.92 ± 2.23	23.20 ± 2.05

*Significant at $p < 0.05$

The volumetric moisture content (θ_v) remained constant at around 30 % for all the surfaces however, that percentage corresponds to levels of saturation of approximately 80, 70 and 60 % for the Sand, the Sandy Loam and the Clay Loam condition, respectively. Measurements of hardness and shear strength before player testing were no different across each surface and between different surfaces, regardless of the movement performed. From a biomechanical point of view, uniform surface mechanical properties are required along the runway. This allows players to perform their movements without interruption from variation in surface properties that could cause undesirable adaptations in movement performance. The measurements taken on the turf trays in the runway before playing testing (initial hardness) proved that the surfaces were maintained consistent across each condition and that the force plate trays were representative of each condition. This adds confidence to the biomechanical findings of the study.

After player running testing, and accounting for the change in moisture of the different treatments, values for final hardness were significantly higher for the Clay Loam compared to the Sand and the Sandy Loam as is shown in Figure 3.14. Nevertheless, according to the calibration certificate of the Clegg hammer used (see Appendix C), ± 10 G is assumed as a typical error that suggests that the differences in compaction occurred, although statistically significant, were small in practical terms. The Clay Loam condition presented the lowest resistance to compaction under the running load for a wider range of moisture content (see Proctor test in Figure 3.13). This was supported by a significantly greater difference in hardness for this condition.

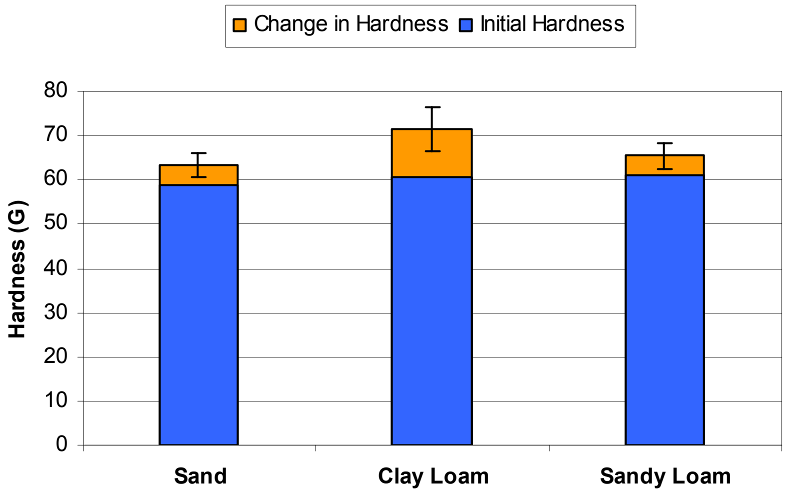


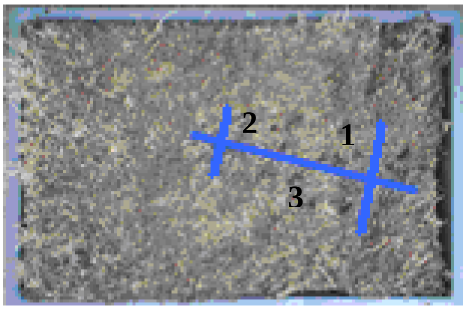
Figure 3.14 Group mean hardness values for running before and after player testing. Errorbars represent means and standard errors, respectively.

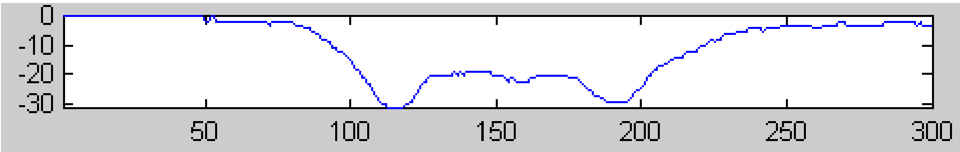
As mentioned before, different textures and densities would suggest surfaces with different mechanical behaviours (cushioning and frictional properties) for the variety of natural turf conditions tested. It could have been that despite the mentioned differences, the turf conditions were too similar and the mechanical differences too subtle for detection. It may be that the devices from the standard techniques used for assessing NTPs, such as the Clegg hammer and the shear vane, were limited for assessing the mechanical properties of the range of NTPs within the experiment.

The 0.5 kg Clegg hammer measures maximum deceleration for a relatively light missile which does not penetrate the soil and hence may be influenced more by the grass and thatch than the soil when measuring ground hardness. A heavier hammer such as the 2.25 kg version might have been more suitable. The shear vane device used appeared sometimes to be only half-sunk in the ground due to an uneven thickness of soil, especially after the turning movement was performed where the players left an inclined plane on the trays as a result from the change in running direction. This would explain why for turning, the surfaces gave more inconsistent and greater readings of hardness and shear strength after player testing compared to before testing. A lower area in contact with the ground implies a smaller shear strength measured by the device. Higher shear strength would have been expected from a more compacted surface after playing testing otherwise. The lack of a flat surface could be reason to also explain the inconsistent data measured from the Clegg hammer for turning.

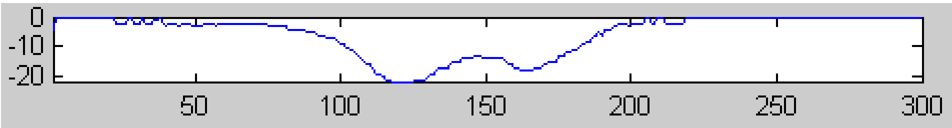
Footprint analysis

The analysis performed on a single Clay Loam force plate tray used for running is presented next to show the methodology that was proposed in Section 3.3.4. A set of three digitalized footprint profiles is shown in the Figure 3.15.

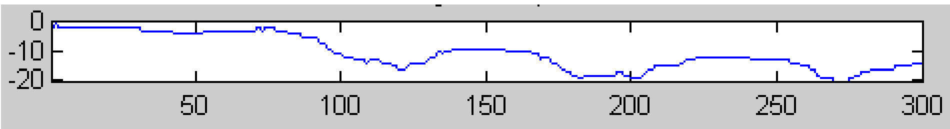




1. Transversally to the foot, on the fore foot area



2. Transversally to the foot, on the rear foot area (heel area)



3. Lengthwise to the foot

Figure 3.15 Digitized profiles (lower images) to determine soil deformation of a Clay tray (top) after player running. The blue lines represent the profile measurements taken. Ordinate and abscissa axes represent depths and longitudes, respectively (all measurements in mm).

Table 3.5 shows the different deformation areas calculated from the image analysis of the digitized profiles shown in Figure 3.15.

Table 3.5 Soil deformation areas.

	Traversally to the Foot		**Lengthwise to the Foot**
	Rear Foot	**Fore Foot**	
Area (mm^2)	1530	2940	2910

The profiles show the depressions in the soil created by the boot sole and some of the studs. This soil deformation was found to be greater for the fore-foot (ball of foot and toes area), up to 30 mm depth, compared to the rear-foot (heel area), up to 20 mm depth. This suggests that greater pressure was applied on the fore-foot for this particular player running on this particular condition. A huge variation in the location of the footprints across the trays was found regardless the surface condition. Ten different footsteps were performed on each force plate tray and a single foot depression did not consistently occur during a particular movement sequence for a player. This caused the footprint areas above ending in an indefinite number of area values leaving the soil deformation undetermined. Unfortunately, it was not possible to develop a systematic methodology to decide which references to take in order to compare the different profiles in a consistent way. Therefore, the analysis was terminated and the approach was considered to be unsuccessful.

3.4.3. Biomechanical kinetic and kinematic data

Force plate: ground reaction forces

The movements performed were described in terms of the vertical (z) and horizontal (y) ground reaction forces (GRF). For running, analysis of the 'group mean player' revealed that two different vertical ground reaction forces time-histories typically occurred. As shown in Figure 3.16, for some players, a two peak profile with first an accentuated passive peak (that relates to foot impact on landing) occurred, followed by a second active peak (that relates to foot push-off). For other players, a single active peak profile took place between the initial ground contact and the foot-off phase. The peak vertical force for running (RN F_z) yielded an average of just over 2.5 BW. The analysis of the anterior-posterior horizontal force for running (RN F_y), revealed a first passive peak (that refers to foot braking) followed by an active peak (that refers to the change in the running direction) of just less than half of the player bodyweight. The ground reaction contact time for running was approximately 0.25 seconds.

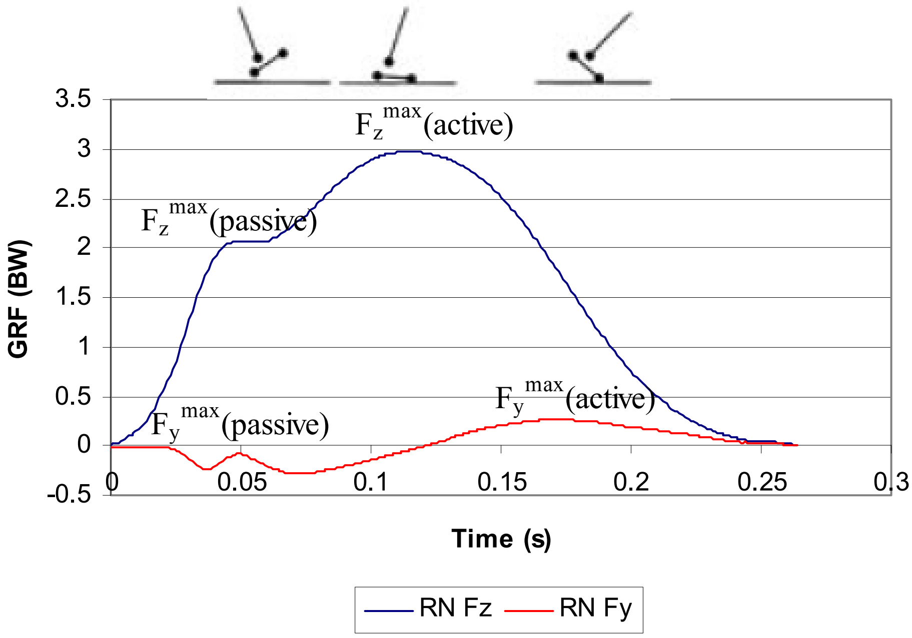


Figure 3.16 Typical vertical (Fz) and horizontal (Fy) GRF-time history profiles for running (RN).

For turning, analysis of the group mean revealed that a single vertical force (TN F_z) time-history typically occurred. As shown in Figure 3.17, first an accentuated passive peak (that relates to foot impact on landing) occurred followed by a second active peak of a lower magnitude (that relates to foot push-off). The peak vertical force magnitudes for turning (TN F_z) yielded an average of just over two times the player bodyweight. The anterior-posterior horizontal force for turning (TN F_y) showed a similar pattern to running in that a first passive peak of just less than the player bodyweight (that refers to foot braking) occurred followed by an active peak of a lower magnitude (that refers to the change in the running direction). The ground reaction contact time for turning was approximately 0.6 seconds.

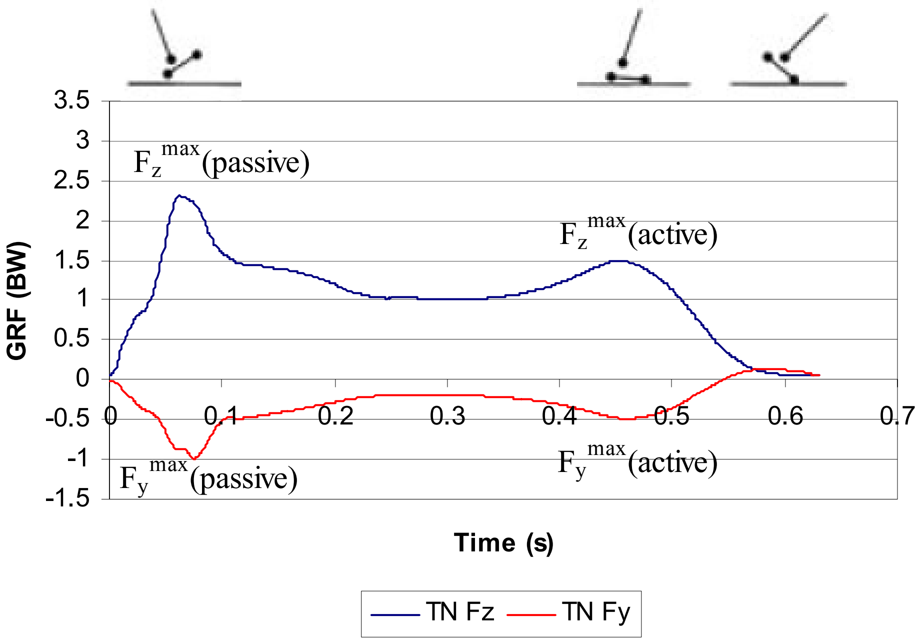


Figure 3.17 Typical vertical (Fz) and horizontal (Fy) Ground Reaction Force-time history profiles for turning (TN).

A summary of the GRF results from an ANOVA ($p < 0.05$) for each movement and surface based on selected variables is presented in the Table 3.6.

Table 3.6 Group mean and standard error for force plate data for 9 players running and turning.

Kinetic variables	Sand	Clay Loam	Sandy Loam
Running			
F_z^{max} (BW)	2.70 ± 0.02	2.71 ± 0.03	2.70 ± 0.02
$t\_F_z^{max}$ (s)	0.113 ± 0.002	0.114 ± 0.002	0.114 ± 0.002
dF_z^{max} (BW s^{-1})*	105.11 ± 3.05	94.96 ± 4.19	98.02 ± 3.76
$t\_dF_z^{max}$ (s)*	0.032 ± 0.001	0.028 ± 0.001	0.031 ± 0.001
F_y^{max} (BW)	0.24 ± 0.01	0.22 ± 0.01	0.24 ± 0.01
$t\_F_z^{max}$ (s)	0.068 ± 0.002	0.067 ± 0.002	0.068 ± 0.002
dF_y^{max} (BW s^{-1})	3.80 ± 1.20	3.81 ± 1.66	3.83 ± 1.30
$t\_dF_y^{max}$ (s)	0.041 ± 0.001	0.039 ± 0.001	0.039 ± 0.001
$(F_y / F_z)^{max}$	0.11 ± 0.01	0.10 ± 0.01	0.11 ± 0.01
$t\_(F_y / F_z)^{max}$	0.067 ± 0.001	0.065 ± 0.001	0.070 ± 0.001
Turning			
F_z^{max} (BW)	2.33 ± 0.07	2.32 ± 0.07	2.33 ± 0.07
$t\_F_z^{max}$ (s)	0.088 ± 0.002	0.086 ± 0.002	0.086 ± 0.002
dF_z^{max} (BW s^{-1})	97.89 ± 5.70	110.31 ± 9.05	102.33 ± 7.06
$t\_dF_z^{max}$ (s)	0.039 ± 0.001	0.038 ± 0.001	0.039 ± 0.001
F_y^{max} (BW)	0.87 ± 0.02	0.88 ± 0.02	0.88 ± 0.02
$t\_F_z^{max}$ (s)	0.102 ± 0.002	0.101 ± 0.002	0.103 ± 0.002
dF_y^{max} (BW s^{-1})	14.13 ± 0.66	15.86 ± 1.14	15.36 ± 0.77
$t\_dF_y^{max}$ (s)	0.045 ± 0.001	0.046 ± 0.001	0.045 ± 0.001
$(F_y / F_z)^{max}$	0.38 ± 0.01	0.37 ± 0.01	0.38 ± 0.01
$t\_(F_y / F_z)^{max}$	0.085 ± 0.001	0.083 ± 0.001	0.086 ± 0.001

*Significant at $p < 0.05$

Analysis of group mean data revealed that F_y^{max} and the $(F_y / F_z)^{max}$ ratio were found to be more than three times higher, on average, for turning than running. The peak vertical force (F_z^{max}), the peak horizontal force (F_y^{max}), the peak ratio between horizontal and vertical force $(F_y / F_z)^{max}$ and their times of occurrence did not vary significantly with changes in surface. However, significant differences were noticed between surfaces for peak vertical rate-of-loading (dF_z^{max}) and its time of occurrence ($t\_dF_z^{max}$). The Sand condition resulted in a significantly greater (10%) vertical rate-of-loading occurring later in time compared to the Clay Loam and Sandy Loam as illustrated in Figure 3.18. The peak horizontal rate of loading (dF_y^{max}) remained consistent between surfaces.

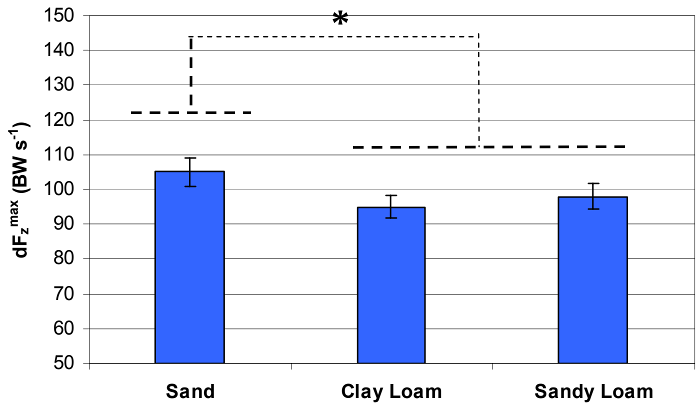


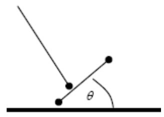
Figure 3.18 Group mean peak vertical rate-of-loading (dF_z^{max}) for running from the force plate. Errorbars represent means and standard errors, respectively. * represents means separated by the LSD at $p = 0.05$.

Infrared cameras: movement analysis

A summary of the kinematic data with mean and standard error values from an ANOVA ($p < 0.05$) for running on each of the surfaces based on selected variables is presented in Table 3.7. An angular convention is also presented to assist data interpretation.

Table 3.7 Group mean and standard error data for joint/segment angles and angular velocities for 9 players running.

Kinematic variables	Sand	Clay Loam	Sandy Loam
φ^{i} (deg)	15.24 ± 0.65	13.97 ± 0.60	14.70 ± 0.63
$d\varphi^{max}$ (deg s^{-1})	238.39 ± 5.15	238.59 ± 5.72	249.64 ± 6.30
dh_z^{i} (m s^{-1})	0.51 ± 0.10	0.50 ± 0.10	0.54 ± 0.10
α^{i} (deg)	2.36 ± 0.83	0.62 ± 0.88	1.18 ± 0.81
α^{max} (deg)	13.90 ± 0.90	14.22 ± 0.89	14.01 ± 0.91
t_α^{max} (s)	0.147 ± 0.002	0.149 ± 0.002	0.147 ± 0.001
α^{ROM} (deg)	11.54 ± 0.32	13.60 ± 0.41	12.83 ± 0.36
$d\alpha^{max}$ (deg s^{-1})	231.47 ± 3.43	243.50 ± 2.29	237.20 ± 2.86
$t\_d\alpha^{max}$ (s)	0.099 ± 0.001	0.095 ± 0.001	0.092 ± 0.001
κ^{i} (deg)	10.89 ± 0.43	10.53 ± 0.60	10.60 ± 0.48
κ^{max} (deg)	34.64 ± 0.51	35.30 ± 0.63	34.86 ± 0.41
t_κ^{max} (s)	0.118 ± 0.001	0.115 ± 0.001	0.114 ± 0.001
κ^{ROM} (deg)	23.75 ± 0.63	24.76 ± 0.57	24.26 ± 0.53
$d\kappa^{max}$ (deg s^{-1})	311.11 ± 5.15	305.95 ± 6.87	310.54 ± 5.72
$t\_d\kappa^{max}$ (s)	0.060 ± 0.001	0.054 ± 0.001	0.051 ± 0.001



No differences were measured for the initial foot angle (φ^{i}), peak foot angular velocity ($d\varphi^{max}$) and heel impact vertical velocity (dh_z^{i}) across surfaces. Initial and peak ankle and knee joint angles (α^{i}, α^{max}, κ^{i}, κ^{max}) and angular velocities ($d\alpha^{max}$, $d\kappa^{max}$) also remained at similar levels with change in surface. Ankle range of movement (ROM) appeared to be lower on the Sand surface compared to the Clay Loam surface however this reduction was not significant at a confidence level of 95%. All of which indicates that no apparent kinematic adjustments took place with the change in surface.

All the results presented in this study have been obtained following a group player analysis, this carries the disadvantage that individual features are lost when one value is used to represent a number of individuals (Bates, 1996).

However, the use of group mean analysis is justifiable in order to generalize research findings to a wider population.

The kinetic and kinematic data presented demonstrate that typical mean force-time history shape and magnitudes of ground reaction forces together with knee and ankle joint variables have been achieved from players performing typical sports movements on a variety of NTPs in the biomechanics laboratory. These values compare well to those obtained from the pilot experiment (Stiles et al., 2006) and the studies presented in the literature (Miller, 1990; Coyle and Lake, 1999), confirming that the kinetics and kinematics of running and turning have been satisfactorily reproduced in this experiment.

Vertical force components can be linked to the cushioning properties of the surfaces, whereas the horizontal ground reaction forces can be related to the frictional properties. The fact that values of peak vertical and horizontal force were maintained constant with the change in surface can be related to the hypothesis that the GRFs represent the acceleration of the total-body centre of gravity and, it appears that this acceleration is kept at consistent levels despite changes in the impacting interface (Bobbert et al., 1992). Despite the fact that no kinematic adjustments were observed on the different surfaces, it has been suggested in the literature that similar impact forces across conditions are achieved by adjustments in running kinematics, compensating for changes in stiffness of the impact interface, varying the lower extremity geometry and impact velocity of the body immediately before ground contact (Dixon & Stiles, 2001).

Loading rates, as seen for the peak vertical rate-of-loading (dF_z^{max}), have been found to be more sensitive to changes in surfaces than ground reaction forces alone. The use of the loading rates simplifies the loading phase of the GRF and it overcomes the difficulty of choosing between active and passive forces (not always present) to develop the kinetic analysis. Loading rates represent how fast the forces are applied by the player over a specific surface and also how quick the energy is returned back to the player. The results so far suggest that the loading rates may have an important role controlling the occurrence of injury in running. A more cushioning surface will work to decrease the forces between the body and the surface by increasing the time of collision, i.e. reducing the loading rate. Likewise, the shorter the impact time, the greater the loading rate, the smaller the cushioning is and so the bigger risk may be for the player. It is hypothesized that the NTPs tested in the project present different resistance to deformation by an applied force, that is, different elastic stiffness and plastic deformation and that this is the cause why players alter their loading rates for different surfaces.

Insole devices: in-shoe forces and pressure

In addition to analysis of the ground reaction force profile, the pressure under the foot was analysed to aid kinetic characterisation, showing the progression of load per unit of time during ground contact. A description of a running step follows next based on Figure 3.19 that illustrates typical force, contact area and pressure-time histories during running. The variables are split into two components corresponding to the rear-foot and fore-foot. Total values of force, area and pressure come from to the contribution of the two areas at any given time. When a player impacts the surface, first, the rear foot (heel area) strikes the ground and the force in the heel area increases reaching a maximum of 1 BW at around 50 ms. This creates a first peak pressure around the heel area occurring at approximately the time of heel peak force (the time of peak passive force where present). By the time the rear-foot peak force decreases, the force in the fore-foot (ball of the foot and toes area) begins to increase and greater peak force and peak pressure occur at the point of foot push-off. The maximum contact area is reached when the rear-foot coincides with the fore-foot. Then the fore-foot remains in contact for longer time until foot-off. The pattern described is typical of a heel-toe running style. The lack of the peak passive force usually seen in heel-toe strikers may be due to a lower data capture rate of the insole system compared to the force plate as was illustrated in Figure 3.16. In general terms, the average and peak force and pressure around the fore-foot is bigger than for the rear-foot.

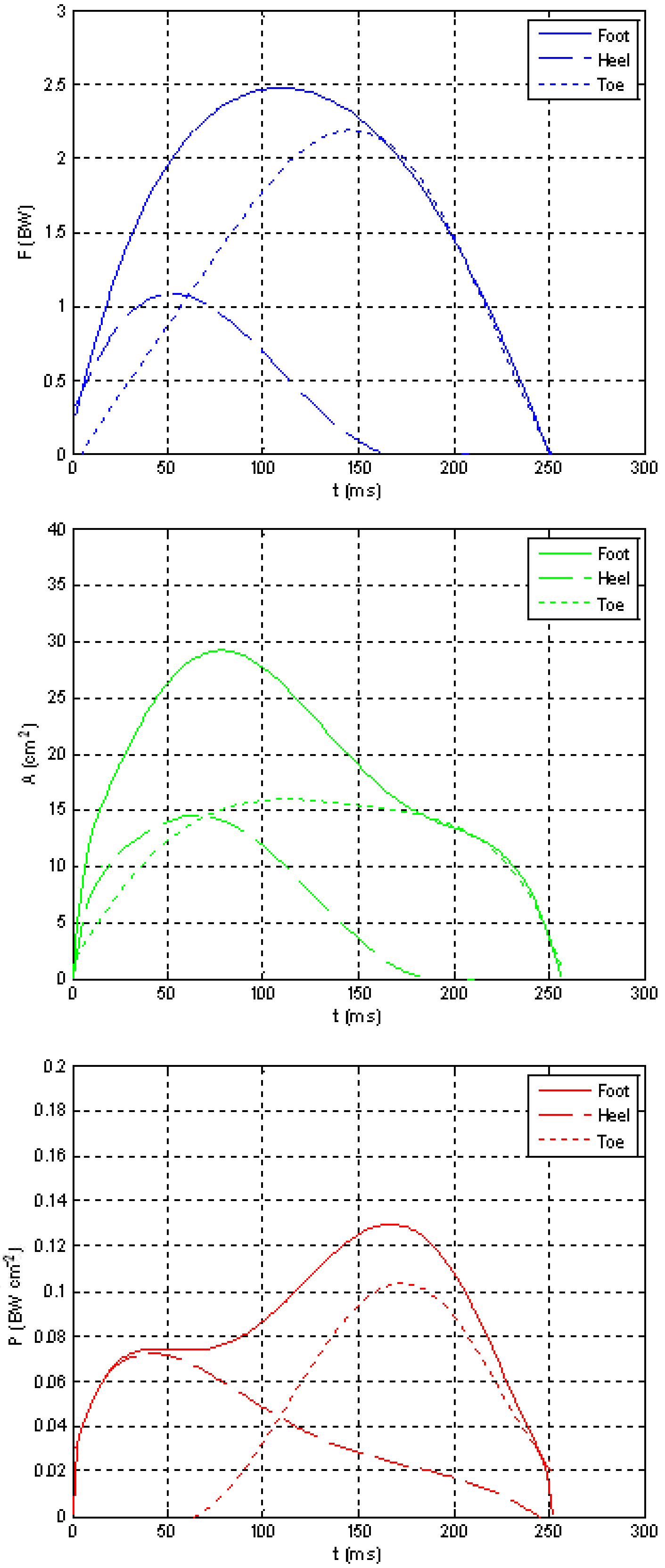


Figure 3.19 Force, contact area and pressure during running for two anatomic parts within the foot from a typical player trial.

Kinetic pressure data were collected for 3 conditions and 2 movements, but due to the limited resources and time available, the pressure analysis was only carried out on the Sand and Clay Loam conditions for the running movement. These surfaces represented extremes in terms of the mechanical properties of the NTPs involved in the study. Running was selected on the basis that the force plate data for running, unlike for turning, revealed significant differences. A preliminary analysis showed no significant differences between conditions in terms of pressure (ANOVA ($p < 0.05$), see Appendix D).

3.4.4. Biomechanical integrated analysis

The treatment structure revealed very few differences among soils in the ANOVA. What is causing variation in the data and what is that variation related to? Alternative statistical techniques make it possible to explain the variation in the data. Hierarchical cluster analysis explores the structure of the variation. Further statistical analysis integrated kinetic and kinematic data. All the data for running (Sand and Clay Loam conditions only) were normalised to have a mean of 0 and a standard deviation of 1, thus maintaining the variation in the variables, and then a distance matrix was generated. The clusters were assigned based on the biggest difference resulting in the largest Euclidean distances in this matrix ('Dissimilarity', Figure 3.20).

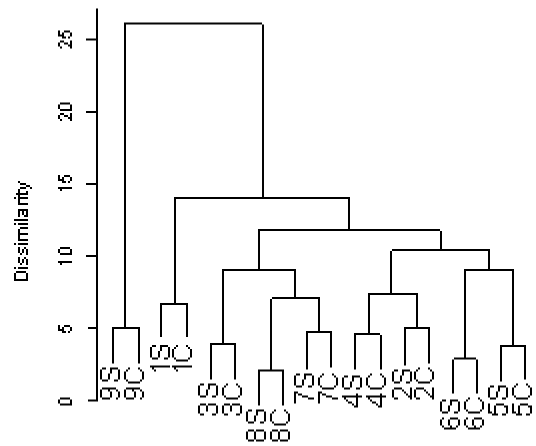


Figure 3.20 First data partition for running on the Sand and Clay Loam conditions showing Player (subject) 9 is different. For each subject, Sand and Clay Loam conditions were found to be different (S and C, respectively).

The analysis of the variation in the peak foot pressure data (PkP) presented in Figure 3.21, revealed that the range of PkP for Player 9 was unlike the typical pressure range for all the other players. It is believed that insole might have worn out and failed for Player 9 who the last subject using the pressure systems.

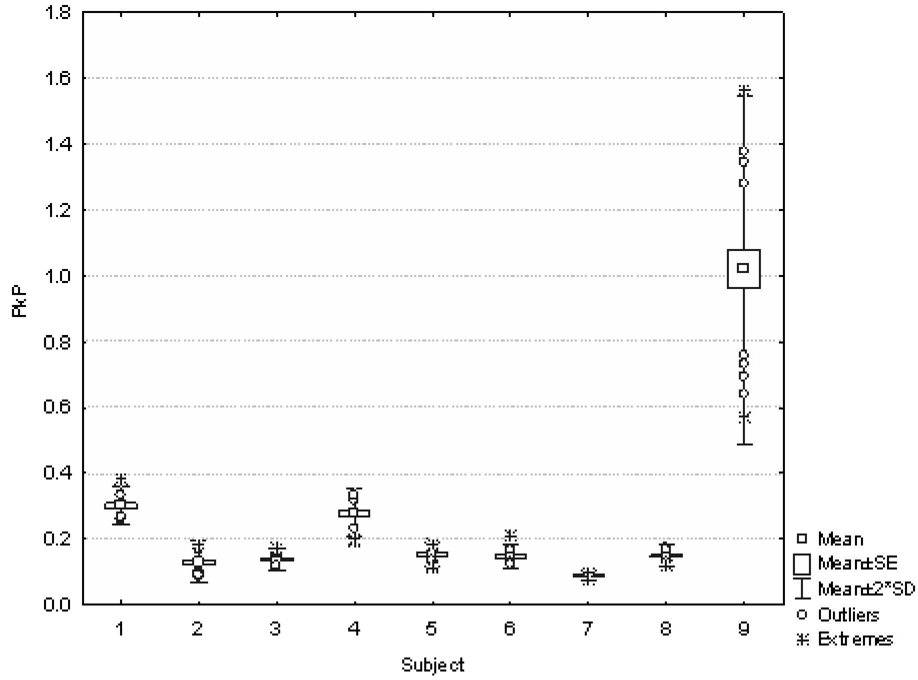


Figure 3.21 Player box plots for peak foot pressure data (P^{max}).

Player 9 was therefore excluded from any post-hoc statistical analysis as his mean values were significantly different from the whole group. Data for the 8 remaining players were divided again into Subgroup A that included players 1,2,3 and 7 and Subgroup B that included players 4,5,6 and 8 as shown in Figure 3.22. Table 3.8 details the group mean data derived from the GLM developed following the clustering analysis.

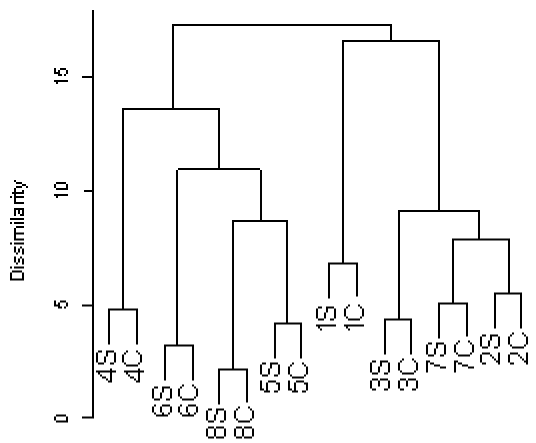


Figure 3.22 Second data partition for running on the Sand and Clay Loam conditions showing how the data can be grouped into Subgroup A consisting of players 1,2,3 and 7 and Subgroup B consisting of players 4,5,6 and 8.

Table 3.8 Group mean and standard error kinetic and kinematic data for 8 players running split into Subgroups using hierarchical cluster analysis. Subgroup A: Players 1,2,3 & 7. Subgroup B: Players 4,5,6 & 8.

	Sand		Clay Loam	
	Subgroup A	**Subgroup B**	**Subgroup A**	**Subgroup B**
Force Plate				
F_z^{max} (BW)	2.57 ± 0.03	2.73 ± 0.03	2.61 ± 0.03	2.71 ± 0.03
$t\_F_z^{max}$ (s)	0.112 ± 0.003	0.117 ± 0.002	0.118 ± 0.002	0.116 ± 0.002
dF_z^{max} (BW s^{-1})*	116.42 ± 5.72	88.08 ± 5.54	95.59 ± 4.63	92.27 ± 5.24
$t\_dF_z^{max}$ (s)*	0.036 ± 0.005	0.035 ± 0.001	0.031 ± 0.001	0.031 ± 0.003
F_v^{max} (BW)	0.32 ± 0.01	0.36 ± 0.01	0.32 ± 0.01	0.34 ± 0.01
$t\_F_z^{max}$ (s)	0.066 ± 0.002	0.068 ± 0.002	0.068 ± 0.002	0.065 ± 0.003
dF_v^{max} (BW s^{-1})	3.78 ± 2.02	3.82 ± 1.69	3.80 ± 2.09	3.78 ± 2.98
$t\_dF_v^{max}$ (s)	0.048 ± 0.006	0.049 ± 0.004	0.043 ± 0.002	0.044 ± 0.004
$(F_V / F_Z)^{max}$	0.119 ± 0.007	0.133 ± 0.005	0.121 ± 0.008	0.134 ± 0.005
$t\_(F_V / F_Z)^{max}$	0.065 ± 0.001	0.071 ± 0.001	0.065 ± 0.001	0.068 ± 0.002
Insole System				
F_z^{max} (BW)	2.54 ± 0.03	2.69 ± 0.03	2.58 ± 0.03	2.67 ± 0.03
$t\_F_z^{max}$ (s)	0.105 ± 0.007	0.107 ± 0.005	0.108 ± 0.007	0.102 ± 0.005
dF_z^{max} (BW s^{-1})*	153.18 ± 7.17	61.48 ± 4.62	125.05 ± 6.49	60.18 ± 6.01
$t\_dF_z^{max}$ (s)*	0.036 ± 0.002	0.033 ± 0.004	0.027 ± 0.001	0.031 ± 0.002
A^{max} (mm^2)	4151.61 ± 97.40	4676.92 ± 141.03	4269.32 ± 107.18	4550.41 ± 181.35
$\bar{A}$ (mm^2)	2577.11 ± 58.87	3116.24 ± 97.51	2629.32 ± 58.47	2994.54 ± 118.93
P^{max} (BW mm^{-2})	19.56 ± 0.88	16.95 ± 1.35	19.24 ± 1.08	17.77 ± 1.32
t_P^{max} (s)	0.167 ± 0.009	0.151 ± 0.005	0.162 ± 0.009	0.161 ± 0.006
dP^{max} (BW mm^{-2} s^{-1})*	0.78 ± 0.06	0.29 ± 0.06	0.61 ± 0.06	0.30 ± 0.04
t_dP^{max} (s)*	0.033 ± 0.001	0.035 ± 0.003	0.026 ± 0.002	0.025 ± 0.004
P_R^{max} (BW mm^{-2})	11.08 ± 0.95	8.93 ± 0.87	11.69 ± 0.87	10.17 ± 0.84
$t\_P_R^{max}$ (s)	0.048 ± 0.001	0.044 ± 0.007	0.052 ± 0.001	0.054 ± 0.007
dP_R^{max} (BW mm^{-2} s^{-1})*	0.75 ± 0.07	0.28 ± 0.11	0.56 ± 0.07	0.26 ± 0.09
$t\_dP_R^{max}$ (s)*	0.016 ± 0.001	0.014 ± 0.001	0.016 ± 0.001	0.015 ± 0.004
P_F^{max} (BW mm^{-2})	14.54 ± 0.80	15.16 ± 1.25	13.39 ± 1.04	13.97 ± 1.28
$t\_P_F^{max}$ (s)	0.122 ± 0.004	0.147 ± 0.004	0.131 ± 0.003	0.151 ± 0.004
dP_F^{max} (BW mm^{-2} s^{-1})*	0.64 ± 0.18	0.24 ± 0.03	0.49 ± 0.15	0.20 ± 0.03
$t\_dP_F^{max}$ (s)*	0.053 ± 0.003	0.057 ± 0.007	0.051 ± 0.002	0.053 ± 0.006
Infrared Cameras				
φ^i (deg)	19.24 ± 2.27	14.05 ± 1.94	17.09 ± 2.82	13.24 ± 1.70
$d\varphi^{max}$ (deg s^{-1})	262.69 ± 25.85	230.00 ± 25.70	273.34 ± 33.00	222.19 ± 17.00
dh_z' (m s^{-1})	0.57 ± 0.02	0.49 ± 0.06	0.46 ± 0.03	0.56 ± 0.02
α^i (deg)	21.52 ± 2.42	1.74 ± 7.71	20.09 ± 2.56	0.77 ± 7.61
α^{max} (deg)	33.83 ± 3.82	13.63 ± 7.49	33.59 ± 3.18	14.21 ± 8.24
t_α^{max} (s)	0.146 ± 0.002	0.147 ± 0.002	0.149 ± 0.002	0.147 ± 0.002
α^{ROM} (deg)	12.24 ± 2.12	11.73 ± 0.44	13.45 ± 1.91	13.59 ± 2.32
$d\alpha^{max}$ (deg s^{-1})	240.05 ± 10.64	235.82 ± 17.65	250.23 ± 12.59	240.23 ± 9.69
$t\_d\alpha^{max}$ (s)	0.098 ± 0.001	0.099 ± 0.001	0.094 ± 0.001	0.095 ± 0.001
κ^i (deg)	16.69 ± 3.70	10.47 ± 3.85	16.36 ± 4.05	10.85 ± 3.41
κ^{max} (deg)	44.15 ± 3.18	33.45 ± 5.98	43.67 ± 2.93	34.72 ± 5.74
t_κ^{max} (s)	0.118 ± 0.001	0.116 ± 0.001	0.114 ± 0.001	0.115 ± 0.001
κ^{ROM} (deg)	27.60 ± 1.34	23.12 ± 2.33	28.35 ± 1.46	23.85 ± 2.03
$d\kappa^{max}$ (deg s^{-1})	349.26 ± 13.97	299.51 ± 16.28	352.95 ± 23.81	282.18 ± 30.63
$t\_d\kappa^{max}$ (s)	0.060 ± 0.001	0.058 ± 0.001	0.054 ± 0.001	0.056 ± 0.001

Significant level at $*p < 0.05$ for surface x subgroup interaction

In the force plate data, the peak horizontal force (F_y^{max}), the horizontal rate-of-loading (dF_y^{max}), the ratio $(F_y / F_z)^{max}$ and their times of occurrence were maintained at similar levels across surfaces and subgroups (A and B). No significant difference was found between surface types for peak force (F_z^{max}), however Subgroup A players yielded significantly lower values of F_z^{max} than Subgroup B. The time of F_z^{max} was however maintained at similar values between surfaces and subgroups. A significant interaction between surface type and subgroups was found in terms of the peak vertical rate-of-loading (dF_z^{max}). Thus, significantly higher values of dF_z^{max} occurring later in time were found for the Sand condition and for the Subgroup A players.

From the insole system data, the same pattern that was observed for dF_z^{max} in Figure 3.18 was determined after performing the cluster analysis as shown in Figure 3.23. No significant difference for the peak contact area (A^{max}) and the mean contact area ($\bar{A}$) was found with the change in surface. However contact areas yielded significantly lower values for Subgroup A players. The peak pressure (P^{max}) and its time of occurrence (t_P^{max}) remained consistent across conditions and subgroups. The peak pressure rate-of-loading (dP^{max}) presented a similar surface x subgroup interaction showing a trend to mimic vertical loading rate (dF_z^{max}) patterns. Thus, dP^{max} took place later in time and was found to be significantly higher for the Sand condition and for the Subgroup A players. This trend was also confirmed for fore-foot peak pressure rate-of-loading (dP_F^{max}). The rear-foot peak pressure rate-of-loading (dP_R^{max}) showed a significant difference between subgroups but did not show any with the change in surface. The respective pressure times of occurrence (t_dP^{max} and $t\_dP_F^{max}$) for each mask showed that the peak pressure rate-of-loading (dP^{max}) occurred earlier in time for Subgroup B players and for the Clay condition. The times for the remaining variables were non-significant although still consistent with the plots presented in Figure 3.19. The insole systems were proved to match the findings derived from the force plate and typical values from other research (Hennig, 2002; Fork et al., 2006).

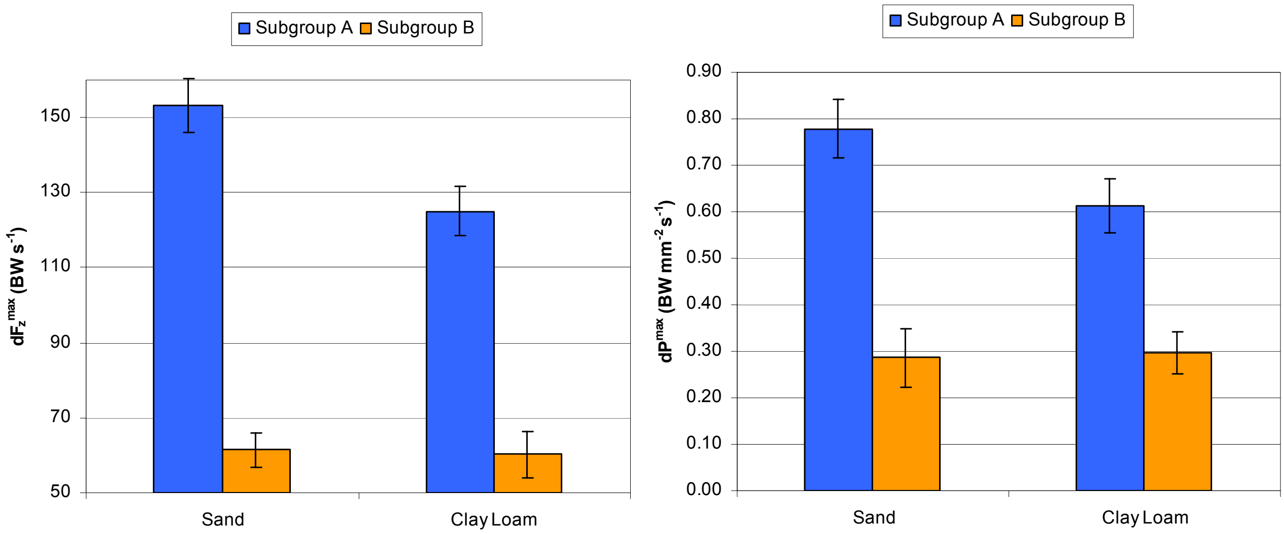


Figure 3.23 Peak vertical rate-of-loading (dF_z^{max}) and peak pressure rate-of-loading (dP^{max}) for the Sand and Clay conditions and for subject Subgroups A and B from the insole system. Errorbars represent means and standard errors, respectively.

As mentioned before, no significant kinematic differences were measured between surfaces which indicate that no apparent kinematic adjustments took place with the change in surface. Instead, there were significant differences in the subgroups that the cluster analysis assigned. Thus, initial and peak joint angles for the ankle and knee (α^i, α^{max}, κ^i, κ^{max}), knee ROM and peak angular joint velocity for the knee ($d\kappa^{max}$) were significantly higher for Subgroup A as can be appreciated in Figure 3.24. The respective times of occurrence for those variables were significantly longer for Subgroup A. All of which indicates that the intrinsic running style of these two subgroups was different. The mean mass of players in Subgroups A was not found to be significantly different from Subgroup B.

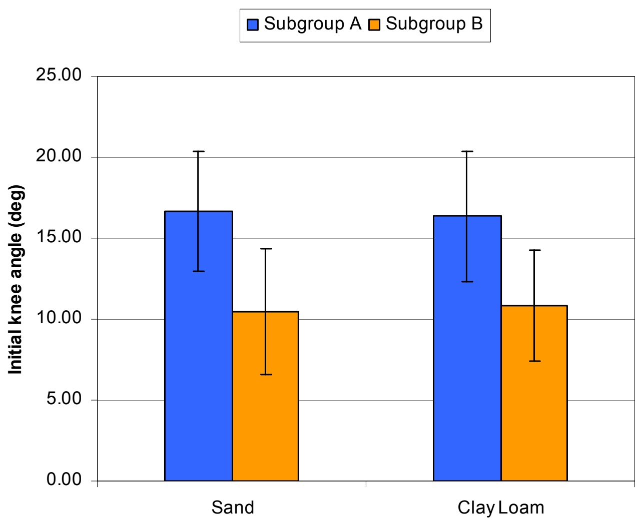


Figure 3.24 The initial knee angle was significantly higher for Subgroup A. No significant difference was found between surfaces.

There is also kinetic evidence to support the hypothesis that players changed their way of running depending on the surface condition and so that it is the surface that is controlling the rate of loading (passively). Thus, Subgroup A showed higher loading and pressure rates (dF_Z^{max}, dP^{max}) and they yielded higher initial joint angles compared to Subgroup B. The low relative magnitude of initial ankle joint angle presented by Subgroup B suggests they represent mid-foot strikes running flat-footed compared to Subgroup A players who present a much higher initial ankle joint angle suggesting they were running heel-toe. However of those kinetic and kinematic differences between player subgroups, there was no kinematic evidence that different subgroups modified their running behaviour based on the surface they performed on.

Based on the study hypotheses, a greater initial knee flexion, lower initial foot and ankle flexion, lower heel and peak foot angular velocities would be expected on the surface showing the greatest rate-of-loading and pressure rate, that is, the Sand condition. The fact that similar joint angles and velocities were observed across surfaces and that no indication of leg geometry adjustments when running on different surfaces that could explain the different loading rates were found, suggests that players prefer to maintain similar leg geometries and stiffness when running on a variety of NTPs which would leave the differences in loading rates found unexplained.

Alternatively, the mechanical properties of the NTPs selected for the research may not have been sufficiently different to elicit changes in player response during running. There is further related evidence from other research that seems to suggest that within the range that NTPs is normally modified to provide a well managed playable surface, all NTPs behave similarly. A study by Dixon et al. (2008) did not show any pressure differences when running on a sandy loam soil (similar to the Sandy Loam condition used for the current study) that ranged from a very lose state to a highly compacted state. However, the presumption that the occurrences of injuries through proposed, and still poorly understood, mechanisms of increased levels of impact and altered joint movement patterns, as a consequence of playing on NTPs, is still prevalent (Hamill et al., 1992; Stergiou and Bates, 1997; Stiles et al., 2006) and so further research is required to completely understand this issue.

3.5. Biomechanical study summary, evaluation and links to the soil Mechanical study

The present study provides a foundation on which to investigate player behaviour with changes in surface using running and turning movements. Two sports-specific movements were analysed in the biomechanics laboratory using a group subject experimental design. Biomechanical analysis allowed characterisation of each movement determined by kinetic and kinematic variables with change in surface to determine whether changes in human response could be detected and wear and degradation differences in surface type determined.

The literature usually cites a lack of correlation between biomechanical and mechanical test findings to relate running to changes in surface properties (Nigg and Yeadon, 1987; Dura et al., 1999; Dixon and Stiles, 2003). In the present study however, mechanical findings showed that Clay Loam appeared to be the softest surface deforming more than the other two conditions during running. Furthermore, biomechanical findings showed that Clay Loam yielded lower loading and pressure rates, which suggests that the stiffness of Clay Loam condition is lower compared to the Sand condition, from which a smaller deformation could therefore be expected, matching again the mechanical findings.

From the time the experiment was designed, special attention was paid to the tray edges. At first it was thought that they could affect the biomechanical experiments since contact with the edges of the turf trays, an event likely to occur given the type of studded footwear used, could cause the players to adjust their natural running or movement behaviour either to avoid the tray edge or to respond to some discomfort noticed and possibly the risk of injury. The turfgrass was left growing over the ends of trays to minimize the adjustments that subjects could still perform affecting their running style in preparation for contact with a different surface. An attempt to cut the edges off resulted in the integrity of the trays being risked which made their manual handling difficult in the laboratory. It could be that the tray edges are the reason why the kinematics did not show any differences between surfaces. But it seems unlikely according to the kinetic findings presented and from observation of running foot-fall in the laboratory. It may be that changing the loading and pressure rate is a mechanism easier to perform by the players or, easier to detect than altering the joints geometry. However, a greater variation in the mechanical properties of the conditions seems to be a more likely cause here.

Nevertheless, to overcome the issue, the use of a non disruptive surface facility similar to the soil bin used by Dixon et al. (2008) where turfgrass could be introduced would be preferred for further research on the subject. It is proposed that future work will assess kinematic response when performing similar movements with changes in natural turf condition from a very wet and very dry Sand and Clay Loam conditions, respectively that will provide a very hard and soft surfaces, with hopefully enough mechanical property range to enable to see kinematic differences. Such extreme conditions may introduce more ethical issues to ensure the safety of players at all times providing, for instance, sufficient stud penetration preventing them from sliding and getting injured.

Surface mechanical data were inconsistent and, although no pressure or kinematic analysis was performed for the turning movement, no agreement with the biomechanical data was determined. However, turning movements that result in a change of direction of the player have been found to yield approximately four times the magnitude of horizontal (braking) forces and loading rates compared to when running. Compared to running, turning imparts greater horizontal forces and rates of loading on the turf thus placing greater reliance on the shear strength properties of the surface in order for the participant to successfully and consistently perform the movement in a stable manner. Given the increased need for the participant to utilise mechanical properties of the turf surface when performing a turning manoeuvre, it is suggested that this movement would provide more scope to study kinematic measures of human response with changes in natural turf condition. Therefore, it is proposed that future work for this project will also assess kinematic response to different turf surfaces when performing turning movements. This analysis has not been possible in this thesis because the determination of the biomechanics parameters is outstanding at this point and falls outside the limit of this thesis.

The mechanical in situ tests utilized have not been found to be accurate enough for the purposes of this study and it is therefore necessary further characterization of the surfaces in a way that enables to fully explain the biomechanical player findings presented. With regards to the mechanical devices used, it is suggested that the use of a heavier hammer (2.25 kg less influenced by the grass instead of 0.5 kg) and a soil penetrometer (instead of the shear vane) would provide more accurate results for further research that wishes to assess mechanical properties of NTPs, specially for turning manoeuvres. Unfortunately, at the time of the experiments were performed however, only the devices used were available.

The chapter has quantified the stresses applied by players when running on NTPs and has been focused on the effect of NTPs on players using the biomechanical laboratory facilities provided at University of Exeter. However, the attempts to monitor surface mechanical properties and its wear and to degradation (such as compaction) have not supplied sufficient information to draw a definitive conclusion about the different behaviour observed for the players and surfaces. More controlled mechanical testing equipment that will reproduce the player inputs measured in the present study (real rates of loading, force and pressure) in the soil dynamics laboratory at Cranfield University will be presented in Chapter 4. Chapter 4 will focus on the effect of the player on NTPs and will provide further information about stiffness differences under typical human stresses when running. This will increase the understanding of the player-surface interaction. The complete mechanical and biomechanical combined approach will define this research study as novel and unique.

4. SOIL MECHANICAL STUDY

4.1. Introduction

The player stresses when performing typical sports movements were recorded in the biomechanics laboratory and reported in Chapter 3 where the effect of different NTPs on player behaviour was discussed. In this chapter, the effect of players on different NTPs was studied by simulating player loadings in the soil dynamics laboratory (Objective 3). The key question was to find out whether the greater rate-of-loading measured in the previous chapter was caused by greater soil stiffness. Following the discussion presented in the biomechanical study (Sections 3.4 & 3.5), the interaction will be focused on the running movement. From a soil mechanical point of view, running is a complicated process where turf and soil are compressed and sheared simultaneously and it is difficult to mimic in a soil laboratory. The present chapter divides player-surface interaction into a vertical interaction where soil is compressed and a horizontal interaction where soil is sheared. Horizontal interaction was approached in accordance with the Mohr-Coulomb theory of soil failure in shear and vertical interaction by means of the response of different NTP construction materials (soils) in uni-axial and tri-axial compression tests with cyclic loading based on layer loading data recorded in the biomechanics experiment.

4.2. Materials and experimental methods

4.2.1. Tri-axial compression

Strength is the ability to carry stress and a measure of the maximum stress state that can be induced in a material without failing. Strength can be referred to in terms of compressive stress or tensile stress but fundamentally it is the ability to resist shear stress that provides strength in soils. In hard, brittle soils, failure may lead to the formation of shear slip surfaces over which a sliding movement takes place. In softer, more plastic soils, failure occurs as a result of internal particle flow (Whitlow, 2001). Soil shear strength is commonly measured in the quasi-static tri-axial compression method, in which a cylindrical soil sample contained within a thin rubber membrane is subjected to an axial load while confined laterally by water at a pressure σ_r (or minimum/minor principal stress, σ_3). Then the load is increased until the soil fails at an axial stress σ_a (or maximum/major principal stress, σ_1) as illustrated in Figure 4.1.

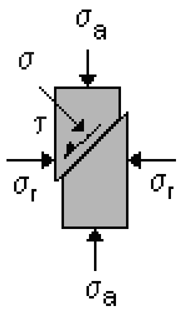


Figure 4.1 Principal stress diagram to which the sample inside the tri-axial compression apparatus is subjected. σ_r and σ_a represent the minimum and maximum principal stresses, respectively. σ and τ represent the normal and shear stresses at failure.

Samples can be either drained or left un-drained. In the present study, un-drained tests were preferred, in keeping with player dynamic loadings, assuming loads are applied so quickly as to not allow soil drainage during loading. The soil is normally found in an un-saturated state in an NTP as a mixture of soil particles together with air and water which is essential to ensure the survival of the grass plant. If such conditions of air and water presence are reproduced in the laboratory when drainage is prevented, then when load is applied to the system, pressure develops in the air, the water and in the solid, and so the applied load will not be wholly supported by the soil particles (Terzaghi, 1943). The effective stress (σ') represents the stress on the solid phase of the soil, that is, on the soil skeleton. To cover un-saturated conditions, Bishop and Blight (1963), assuming the particles and water incompressible, proposed a modified effective stress:

$$\sigma' = \sigma + \chi(u_a - u_w) \qquad \text{(Equation 4.1)}$$

Where σ is the applied total normal stress, u_a is pore air pressure, u_w is the water pressure and χ is a parameter related to the degree of saturation (1 for a saturated soil, 0 for a dry soil), determined experimentally from tri-axial compression tests. As an extension to the above work, Fredlund and Rahardjo (1993) based all of their analysis on unsaturated soils on the theory that soil is a four phase system: soil particles, air, water and contractile skin (the air-water interface). They suggested three possible normal stress variables: 1. $(\sigma - u_w)$ and $(u_a - u_w)$; 2. $(\sigma - u_a)$ and $(u_a - u_w)$ or 3. $(\sigma - u_a)$ and $(\sigma - u_w)$, of which any two could be used to define the stress state of the soil. The pore air pressure (u_a) is required for any case.

Unfortunately, the modifications available to conventional tri-axial equipment to control pore air pressure are not particularly appropriate when dealing with the high strain rates applied by humans as the time for air pressure to move through and equilibrate along the sample takes too long (GDS Instruments, per. comm.) and so no measurement of the pore air pressure was carried out in the present study. Therefore the experiments performed should be viewed as total stress type tests rather than effective stress tests. The material only “feels” the effective stress and not the external or total value of the stress state. The total stress is a contribution of the effective stress, the air and the water pressures as described by Equation 4.1 and therefore the results derived from such tests will only serve as an indication of the soil shear strength since the actual stresses at failure will be unknown (Fredlend & Rahardjo, 1993).

Dynamic Tri-axial Testing System (DYNTTS) overview

The DYNTTS system consists of the following major subsystems (Figure 4.2):

- Actuator unit (1), cell top and balanced ram (2)
- Back pressure controller (3) and cell pressure controller (4)
- PC, High Speed Data Acquisition and Control Card (HSDAC) (5)
- Signal conditioning unit / Digital Transducer Interface (DTI) (6)

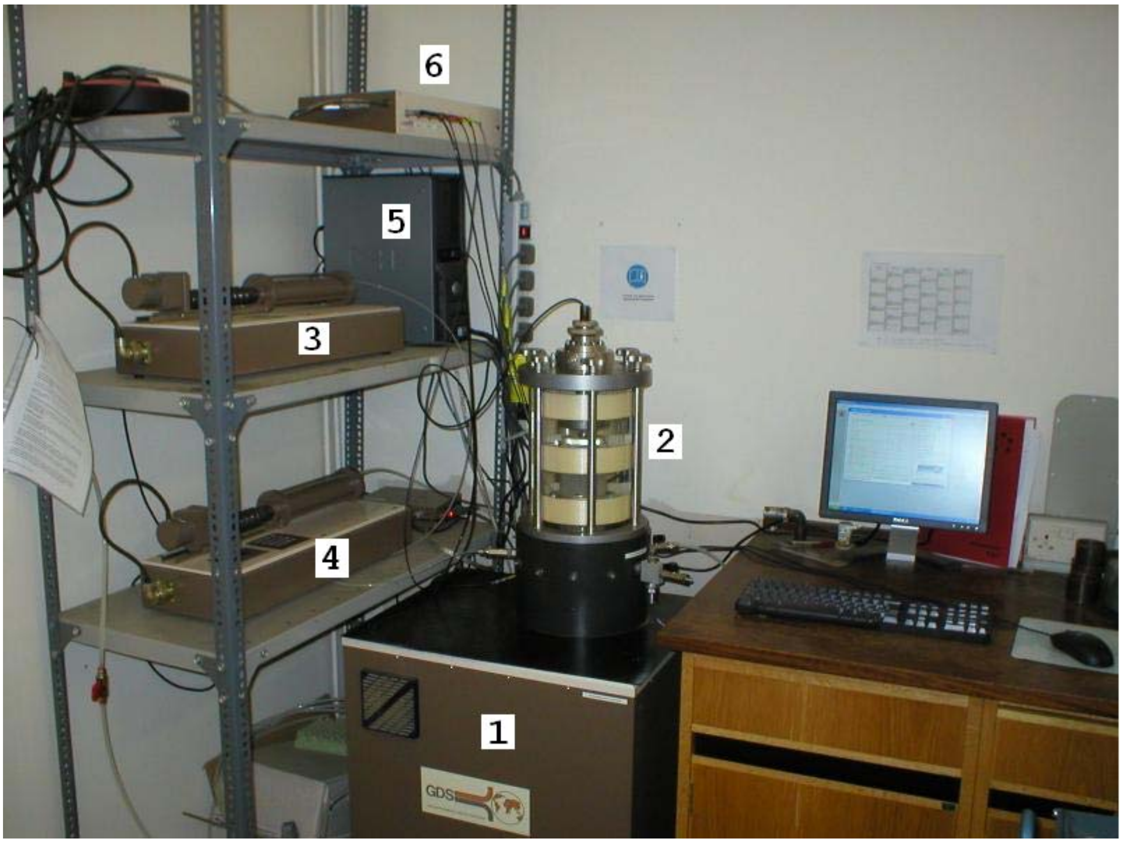


Figure 4.2 The DYNTTS comprises the following separate items: a tri-axial cell (2) integrated on an axial dynamic actuator (1), a back pressure (3) and a cell pressure (4) controller, a PC-resident data acquisition and control card (5) and a data interface unit for signal conditioning (6). A soil sample specimen can be seen in place.

As described by Menzies et al. (2002), the actuator unit is the main cabinet which houses the axial actuator and on which the cell base is fixed. It consists of a servo-motor which drives a ball screw via a toothed belt and gives dynamic control of axial deformation or axial force to 2 Hz / 10 kN. The axial ram is attached to a thrust-cylinder and ball-nut which is driven by the ball screw. The thrust cylinder is prevented from turning by means of a linear guide connected to the centre plate. The thrust cylinder is connected to the axial ram which passes through the balanced ram arrangement and then through the base of the cell. The base pedestal is connected to the ram. The cell top is fixed on the top of the actuator unit by six tie rods. The actuator unit houses all of the hydraulic connections to the cell, which are back pressure, pore pressure, cell pressure and cell fill / empty connections.

The cell top is removable to allow the test specimen to be put in place. Test specimens of diameter 38, 50, 70 and 100 mm can be accommodated by interchangeable base pedestals and tri-axial extension top caps. The cell includes an internal axial load cell, a pore pressure digital transducer of capacity 2 MPa, and it is connected to a cell pressure and back pressure digital transducers of capacity 2 MPa. Each of them senses pressure from a pressure transducer inside the controller pressure cylinder, converts this into digital form and then turns the motor to increase or decrease the pressure as required.

The cell is provided with a balanced ram to eliminate disturbance to constant cell pressure during dynamic tests. The cell fluid is water. This compensates for the volumetric displacement of the loading ram into or out of the cell. Down the centre of the hollow ram, the cell fluid is hydraulically connected to a chamber through which the ram passes. In this chamber the ram has an annular piston attached to it. The annular area is exactly equal to the area of the ram. When the ram moves in the cell and causes a volume change, the annular piston causes an equal and opposite volume change. In this way the net volume change in the cell is zero. In addition, cell pressure acting on the annular ring automatically compensates for the effect of cell pressure acting on the ram. This means that the axial force capacity of the cell is independent of cell pressure.

The signal conditioning units consist of both analogue and digital signal conditioning. The analogue signal conditioning consists of an eight channel board which supplies excitation to each transducer. This card is installed in a free-standing unit (DTI) which is placed next to the computer. All outputs are conditioned to +/- 10 V for input to the High Speed Data Acquisition and Control (HSDAC) card installed in the computer. The digital signal conditioning is contained in the DTI unit and it consists of a board containing eight channels to interface from the HSDAC card to the motor controller and vice-versa. The HSDAC card is used to control axial controller. For closed loop load control, feedback is taken from the internal load cell output. For closed loop deformation control, feedback is taken from the axial motor high speed shaft encoder. Thus, the system control is shared between the control software (GDSLAB) and the control firmware which resides in the HSDAC card which has an internal memory of 64 kb (Hooker, 2002).

On-board computer control is via one synchronised self calibrating PC-resident 16 bit data acquisition and control card monitoring the input. This card has a 50 kHz capacity digital-analogue conversion rate. The card is dedicated to the logging and control of axial displacement and axial force. All required signal conditioning and motor drive control sub-systems are housed in the integral base unit. The GDSLAB control and data acquisition software package runs on a compatible PC. The software provides on-line graphics and real time logging to hard disc. Saved data may be analysed later by transferring the ASCII text file directly to a spreadsheet or to MATLAB.

The dynamic capability of the system is described in terms of the maximum double amplitude of the axial actuator. The maximum double amplitude when cycling a sinusoidal waveform at 2 Hz is 5 mm, at 1 Hz is 14 mm and at 0.1 Hz is 100 mm. The system performs at speeds defined by these frequencies and double amplitudes. How this translates into axial stress control depends entirely on the soil stiffness and specified axial stress double amplitude. For stiff soils at low axial stress double amplitudes, higher frequencies will be possible than for soft soils at high axial stress double amplitudes. The axial displacement accuracy is 0.07 % and the resolution for displacement and force is 0.08 μm and 0.1 % FRO (Full Range Output), respectively.

4.2.2. Stiffness moduli

The tri-axial stress and strain variables were defined by Whitlow (2001) as follows:

$$q = \sigma_a - \sigma_r \quad \text{(Equation 4.2)}$$

$$p = \frac{1}{3}\left(\sigma_a + 2\sigma_r\right) \quad \text{(Equation 4.3)}$$

$$\sigma_a = \frac{F}{\Delta l} \quad \text{(Equation 4.4)}$$

$$\varepsilon_a = \int_{l_0}^{l} \frac{dl}{l} = \ln\frac{l}{l_0} \quad \text{(Equation 4.5)}$$

$$\varepsilon_s = \frac{2}{3}\left(\varepsilon_a - \varepsilon_r\right) \quad \text{(Equation 4.6)}$$

$$\varepsilon_v = \varepsilon_a + 2\varepsilon_r \quad \text{(Equation 4.7)}$$

Where q is the stress difference or the deviator stress; p is the mean normal stress; σ_a is the axial stress; σ_r is the lateral or radial stress; ε_a is the axial strain; ε_s is the shear strain and ε_v is the volumetric strain. The relationship between the stress and the strain that it causes is termed the stiffness of the material. From the definition of the above parameters, it is possible to express the stiffness moduli and the following relationship between them:

$$K = \frac{dp}{d\varepsilon_v} \quad \text{(Equation 4.8)}$$

$$D = \frac{dq}{d\varepsilon_a} \quad \text{(Equation 4.9)}$$

$$G = \frac{dq}{d\varepsilon_s} \quad \text{(Equation 4.10)}$$

$$G = \frac{E}{2(1+\nu)} \qquad \text{(Equation 4.11)}$$

$$K = \frac{E}{3(1-2\nu)} \qquad \text{(Equation 4.12)}$$

For isotropic elastic deformation, each material has a property that defines its volumetric stiffness (bulk modulus, K) and its shape stiffness (shear modulus, G). These properties determine the constrained elasticity modulus, D and the Poisson's ratio, ν. For an un-confined test (σ_r = 1 kPa), the constrained modulus represents the elasticity modulus or Young's modulus of the material.

In this study, Poisson's ratio and shear modulus were calculated from the Young's modulus and the bulk modulus from Equations 4.15 and 4.16, respectively. True strain was replaced by the engineering strain to simplify calculations. Therefore, every σ-ε relationship that appears in this report is in fact an engineering σ-e relationship:

$$e = \frac{l - l_0}{l_0} \qquad \text{(Equation 4.13)}$$

On the other hand, unlike Hookean materials, the stiffness of soils is not constant for a range of stress-strain values. Soils present a non-elastic behaviour and the stress-strain curve is not straight as the elastic constants vary with stress. Thus, the above described stiffness constants originally defined as tangent moduli were redefined as secant stiffness moduli as follows:

$$K = \frac{\Delta p}{\Delta \varepsilon_v} \qquad \text{(Equation 4.14)}$$

$$D = \frac{\Delta q}{\Delta \varepsilon_a} \qquad \text{(Equation 4.15)}$$

The change from elastic to plastic straining is marked by a change in slope of the stress-strain curve. In this study, this point will be called the yield plastic point and the stress at which occurs, the yield stress. Based on a statistical analysis of the linearity of the data, the yield point in this work represents the end of the linear phase with a tolerance limit of 5% (95% confidence) in both, the isotropic compression and shearing stages. MATLAB scripts were developed for calculating the secant stiffness moduli according to the expressions described above.

4.2.3. Mohr-Coulomb modelling

As mentioned in Section 4.2.1, shear strength is essentially due to the development of frictional resistance between adjacent particles, and the analysis of soil strength is thus normally based on frictional models such as the Mohr-Coulomb model (Fredlund & Rahardjo, 1993). This model replaces the complexity of real soil behaviour by a simplified representation of its shear strength in a linear relationship between normal and shear stresses at failure (Figure 4.1).

$$\sigma = \frac{2c\cos\phi}{1-\sin\phi} + \frac{1+\sin\phi}{1-\sin\phi}\sigma_r \qquad \text{(Equation 4.16)}$$

The axial stress at failure (σ) and radial stresses (σ_r) are usually plotted on the abscissa against shear strength, τ and a Mohr stress circle is drawn through these points. Further tests are then run with a range of values for σ_r and circles are constructed as before. As explained by Terzaghi & Peck (1948), Mohr proposed that the envelope tangentially to those stress circles defines the material strength at failure.

$$\tau = c + \sigma \cdot \tan\phi \qquad \text{(Equation 4.17)}$$

The angle between a strength envelope and the normal stress axis is termed the angle of friction, ϕ and the ordinate value for a zero normal stress is called the cohesion, c (Scott, 2000). The internal friction contribution, that is, the interlocking of particles or the resistance to sliding of one particle over another, is proportional to the normal stress applied. The angle of the plane of failure (α) is a function of the angle of friction (ϕ):

$$\alpha = 45° + \frac{\phi}{2} \qquad \text{(Equation 4.18)}$$

Mohr-Coulomb stress theory was implemented into MATLAB on a stand-alone application that was developed to analyze tri-axial compression data. The piece of software works from a set of up to five axial stresses at failure, at a set of given confining stresses, and it provides the soil strength (τ) as a linear model of the applied vertical stress (σ).

4.2.4. Dynamic compression

Real foot-surface impact implies a continuous change in the contact area during the time of the impact as it was shown in Figure 3.19. The available compression equipment does not allow for a changing loading area. Moreover, there is a rolling movement when running that would require a rotation of the principal stresses that cannot be achieved with the standard compression apparatus available. The DYNTTS system used for the project allows loading a soil sample at a certain rate-of-loading applied over a fixed flat area (a Φ 70 mm cap with an area, $A_{cap} \approx 3900$ mm^2) that compresses the cylindrical soil sample placed underneath.

The aim of the simulation is to replicate the measured loading rates up to the loads applied by the players maintaining the actual stress values. Therefore, not only do the ground reaction forces have to be taken into account in the simulation, but also the contact area involved. From Table 3.8, a representative mean running contact area of around 2900 mm^2 was worked out for simulation purposes. It is important to note that all area values were derived from the pressure insole systems and so they represent the foot area of contact within the boot. The contact area between the outside of the boot and the soil is however required as this is the actual surface in contact with the ground.

To determine the external area of the boot, a stand-alone MATLAB image analysis script was specifically developed. The subroutine assumes total stud penetration and calculates the external contact area of a size 11 boot from a black and white photograph of the boot sole used for the biomechanical experiments (Figure 3.4). A maximum boot contact area of around 5800 mm^2 was calculated (Figure 4.3). Then, for the mentioned mean foot contact area ($\bar{A}$) of 2900 mm^2, and again from Table 3.8, a mean outside boot contact area ($\bar{A}_{boot}$) of approximately 3800 mm^2 was calculated by comparing the maximum outside boot contact area ($A_{boot}^{max} \approx 5800$ mm^2) and the maximum foot contact area ($\bar{A}^{max} \approx 4400$ mm^2) as expressed in Equation 4.19.

$$\bar{A}_{boot} = \bar{A}\cdot\frac{A_{boot}^{max}}{\bar{A}^{max}} = 2900\cdot\frac{5800}{4400}\,mm^2 \approx 3800\,mm^2 \qquad \text{(Equation 4.19)}$$

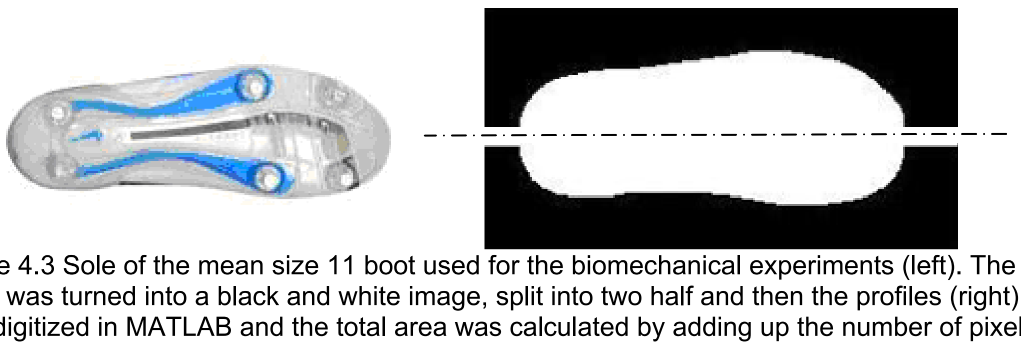


Figure 4.3 Sole of the mean size 11 boot used for the biomechanical experiments (left). The photo was turned into a black and white image, split into two half and then the profiles (right) were digitized in MATLAB and the total area was calculated by adding up the number of pixel between the two profiles.

As mentioned before, in order to simulate player dynamic loading of soil, some other input parameters were required: the peak vertical force (F_z^{max}) and the peak vertical rate-of-loading (dF_z^{max}) applied by the players. These parameters were determined in the biomechanical study presented in Chapter 3. From Table 3.8, a mean maximum vertical force of 2.60 BW and a mean maximum vertical rate-of-loading of around 95 BW s^{-1} were converted from body weight to units of force / time and taken as representative mean values for the dynamic simulation of running. This determined that, for a given mean player weight of 0.78 kN, peak vertical force and rate-of-loading were approximately 2.10 kN and 75 kN s^{-1}, respectively. Thus, from Equation 4.20 it was derived that the axial force for compression ($F_{axial\text{-}comp}$) required to mimic a running strike calculated was approximately 2 kN.

$$F_{axial-comp} = \overline{F}_z^{\max} \cdot \frac{A_{cap}}{\overline{A}_{boot}} = 2.10\,\text{kN} \cdot \frac{3900\,mm^2}{3800\,mm^2} \approx 2\,\text{kN} \quad \text{(Equation 4.20)}$$

The effect of the fore-foot and the rear-foot on surface deformation could be studied for the different running styles found (mid-foot and heel-toe) and also for the different player subgroups, following the approach performed in Chapter 3. In practical terms, this approach would require several different dynamic simulations to be carried out for the NTPs involved in the project. Due to time constraints of the project, a single simulation for the whole group using the mean stresses and contact area values presented was used to develop the methodology.

With regards to the rate-of-loading, due to limitations of the soil mechanics equipment it was not possible to replicate the peak loading rates above mentioned. It is known that a change in strain rate implies a change in the amount of strain experienced by the material (Herrick and Jones, 2002). The working hypothesis was that stiffness increases with loading rate as soil particles would not have enough time to reorganise and accommodate plastic strain at the greater strain rate. This highlights the importance of determining the mechanical properties of sports surfaces at the actual strain rates that players perform in sports. To test soils with the actual player loading rates, a 20 Hz machine is required. Unfortunately, the available equipment was only a 2 Hz machine. A maximum peak loading rate of 6.5 kN s^{-1} was possible, although 10 times less than human loading, this is still four orders of magnitude faster than a typical quasi-static strain rates of 5 x 10^{-4} kN s^{-1} used in ‘quick’-undrained Mohr-Coulomb type strength testing of soils described in previous sections (BS 1377:1990 7/8).

Tri-axial compression: lateral stress issue

In soil granular materials, internal frictional resistance is developed between adjacent grains. Thus, the horizontal pressure is not usually equal to the vertical pressure at the same point, although one is still a function of the other. The magnitude of lateral (horizontal) pressure is dependent on the shear strength of the soil, the lateral strain conditions and the state of equilibrium of the soil.

The strain state relating to lateral pressure calculations refers to elastic equilibrium with no lateral strain taking place (Whitlow, 2001). If the stress state in a soil mass is still below the Mohr-Coulomb failure envelope, the soil is still in elastic equilibrium. The soil mass is said to be in an at-rest state and the horizontal stress is:

$$\sigma_h = K_0 \sigma_v \qquad \text{(Equation 4.21)}$$

Where, σ_v and σ_h are the vertical and horizontal stresses and K_0 is the coefficient of lateral pressure described as a function of the angle of friction (ϕ) of the soil by the following relationship:

$$K_0 = \frac{1-\sin\phi}{1+\sin\phi} \qquad \text{(Equation 4.22)}$$

To simplify the tri-axial testing procedure, a stress condition similar but not identical to the "in situ" condition is often approximated by a mean stress (Head, 1998) and the soil can be subjected to an equal all-round pressure equal to:

$$\frac{\sigma_v\left(1+2k_o\right)}{3} \qquad \text{(Equation 4.23)}$$

In terms of total stresses, the vertical stress can be described as the weight of soil vertically above together with any force acting in the soil surface.

$$\sigma_v = \rho g z + \sigma_{vhuman} \qquad \text{(Equation 4.24)}$$

$$\sigma_v \approx \sigma_{vhuman} = \frac{F_{vhuman}}{A} = \frac{2\,kN}{40x10^{-4}\,m^2} = 500\,kN\,m^{-2} \qquad \text{(Equation 4.25)}$$

Dynamic tri-axial compression was attempted on the Sand soil material, assuming that the gravity stress term in Equation 4.24 was negligible, a maximum vertical stress of 2 kN, a boot mean contact area of 3.8 x 10^{-3} m^2 (calculated in Section 4.2.4) and a typical internal angle of friction of 31.81º (shown in Section 4.3.1) as reasonable values. Thus, following Equation 4.22, a value of mean stress around 250 kPa was obtained as the radial pressure needed for simulation.

$$\frac{500\left(1+2\dfrac{1-\sin\phi}{1+\sin\phi}\right)}{3} \approx 250\,kPa \qquad \text{(Equation 4.26)}$$

Preliminary tests carried out at confining stresses of 100 and 200 kPa failed in the first cycle of loading and it was confirmed that a minimum stress of 250 kPa as calculated by Equation 4.36 was required to perform the tests.

Stress-strain behaviour

Energy can be described as the ability to do work. More work can mean running faster or for longer and therefore relates to sports performance. Energy is transferred in sports from the player body ($W_{athlete}$) to the surface ($\Delta E_{surface}$) and back again (Stefanyshyn et al., 2001). The performance is influenced by the balance between energy return and energy lost during surface deformation.

$$W_{athlete} = \int F \cdot dr = \Delta E_{surfave} \qquad \text{(Equation 4.27)}$$

$$E_{returned} = E_{input} - E_{lost} \qquad \text{(Equation 4.28)}$$

Despite the fact that energy return or the elasticity of NTPs has not been widely investigated (Martin et al., 1993), under repetitive loading it could be expected that the soil will undergo certain unrecoverable or plastic strain in addition to some recoverable or elastic deformation that will be a function of the complex interaction of all the components comprising the NTP. The elasticity of the surface represents the capacity to absorb energy when it is deformed and to return it, and directly correlates to performance and injury prevention: the quicker and greater the energy dissipation, the more shock-absorbent the surface. A too compliant surface can lead to early leg-muscle fatigue (Millet et al., 2006) while a stiffer surface can result in cartilage damage (Orchard, 2001).

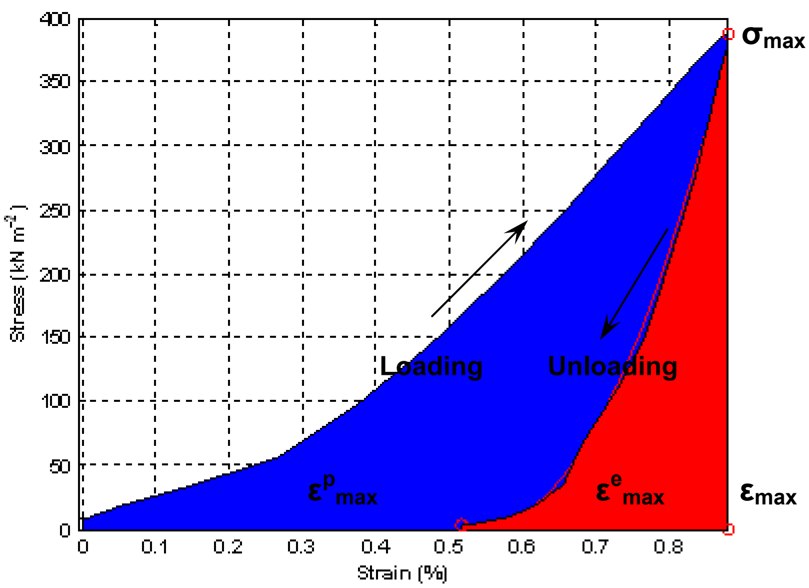


Figure 4.4 Example of a hysteresis energy deformation loop. Blue and red represent plastic energy dissipated and elastic energy recovered during deformation respectively. ε^{e}_{max} and ε^{p}_{max} represents the maximum elastic and plastic strain, respectively in the cycle after a repeated axial cyclic stress (σ_{max}) was imposed.

Soil mechanical stress-strain behaviour is known to be visco-plastic, in that it is partly elastic or reversible in time if the load is removed, but mainly plastic or non-reversible (Hamza et al., 2005). Therefore, under repetitive stressing it could be expected that soil will undergo certain unrecoverable or plastic strain in addition to some recoverable or elastic deformation. The limits and relative proportions between the elastic and the plastic behaviours depend on the complex interaction of all the components comprising the NTP and also on the strain rate at which the soil is deformed, which is a function of the load magnitude and the rate-of-loading (Karmakar & Kushwaha, 2005).

There is no unique way of defining dynamic stress-strain behaviour of soils (Schneider et al. 1999; Assimaki et al., 2000). In the present study, soil response under cyclic loading conditions was characterized in sufficient detail by a dynamic modulus associated with the energy dissipated in one cycle of deformation. This modulus defines soil stiffness and can be seen as a simple estimation of the dynamic elastic modulus. With reference to the hysteresis energy loop (Figure 4.4), a secant dynamic stiffness modulus (k_d) can be calculated as the ratio between the maximum axial stress (σ_{max}) and the maximum strain (ε_{max}) in the cycle after a repeated axial cyclic stress of fixed magnitude.

$$k_d = \frac{\sigma_{\max}}{\varepsilon_{\max}} \qquad \text{(Equation 4.29)}$$

It is expected that after a number of cycles, the soil will reach a steady-state dynamic stiffness, where an increase in load will be required to compact the surface further. The steady-state stiffness will be defined as the maximum dynamic stiffness, k_d^{max}.

4.2.5. Experimental design

Quasi-static testing

In order to characterize the compressive and shear behaviour of different NTPs, under static and dynamic player inputs from running, the Sand and Clay Loam conditions previously presented in Chapter 3 were replicated in the soil laboratory and further investigated by means of compression testing. The soils were reconstituted in a cylindrical mould (Ø 70 x 140 mm) in 8-10 layers of equal depth depending on the initial target density and moisture content.

In addition, some of the Sand samples were seeded with rye grass (Figure 4.5) and maintained following the same process described in Section 3.3.1 until a proper rooting system was developed. The excess of grass was cut off from the both sample ends to ensure good settlement. The removal of the sample from the mould was carried out directly onto the tri-axial platform to minimize sample handling.

Figure 4.5 A total of twelve Sand grass-rooted samples were prepared (left) and tested to assess the effect of grass rooting (right) on shear strength.

The results obtained from the Proctor tests presented in Figure 3.13 were used to select the set of dry bulk densities (ρ_b) and gravimetric moisture contents (θ_m) that define the treatments presented in Table 4.1, which consider the effect of moisture, density and grass rooting in soil shear strength. The S2 treatment represents the maximum density attainable for the sand soil at an optimum moisture content (Table 3.3), whereas the C2 treatment represents a slightly lower density than the Proctor optimum (89%) because the mechanical effort required to achieve the proctor optimum could not be replicated without damage to the sample preparation equipment. S1 and C1 and S3 and C3 treatments represent very dry and very wet conditions, respectively. S4 and C4 treatments represent lower density conditions at the moisture at which the maximum density can be achieved.

Table 4.2 Dry bulk densities (ρ_b) and gravimetric moisture contents (θ_m) for the quasi-static tri-axial compression experiments performed. The S5 condition represents a grass-rooted treatment.

Variable	Sand					Clay Loam			
	S1	S2	S3	S4	S5	C1	C2	C3	C4
ρ_b (g cm^{-3})	1.75	1.75	1.75	1.60	1.75	1.60	1.60	1.60	1.30
θ_m (%)	6.00	11.50	17.00	11.50	11.50	12.00	15.00	18.00	15.00
% Saturation	30	50	80	46	50	40	50	60	42
Grass	-	-	-	-	√	-	-	-	-

The compression tests were carried out using an electromechanical dynamic tri-axial soil testing system (GDS DYNNTS 2Hz 10kN, GDS Instruments Ltd., Hampshire, UK). The experiment proceeded in two stages. For the quasi-static approach, first an isotropic compression was applied and then a deviator stress was applied at a constant axial strain rate of 1 mm / min up to 25 % of the sample length.

For the S2 treatments, the following confining pressures were tested: 50, 100, 200 and 300 kPa. Due to resources and time restrictions only 100 and 300 kPa were tested for the rest of the treatments. Un-confined tests (1 kPa) were carried for all the treatments. The approach was intended for the measurement of total stresses in not completely saturated soil samples, where drainage was not permitted either during the application of the confining stress or during the application of the deviator stress. Each experiment was replicated three times.

A pressure-volume controller regulated the confining pressure by increasing it at a constant rate of 5 kPa / min with a resolution of 1 mm^3 of water exchanged. During the first test stage, the isotropic confining pressure applied, and the volumetric strain achieved (from the volume of water exchanged), were recorded. Deviator stress and axial displacement were recorded during the second stage of the tests. It was assumed that there was no shear failure until the applied stress exceeded the soil yield stress at the point of the maximum deviator stress (the peak stress, q^{max}). During shearing, a correction was made to the major principal stress in the sample to compensate for the membrane resistance to the applied loads, using the Equation 4.30 (Head, 1998):

$$\Delta\sigma_a = \frac{4\varepsilon_a t_o E}{D_o\left(1-\varepsilon_v\right)} \qquad \text{(Equation 4.30)}$$

Where, ε_a and ε_v are the axial and volumetric strain respectively, measured from the beginning of shear, t_o is the thickness of the membrane and D_o is the initial diameter of the sample.

Dynamic testing

In order to investigate the effect of player repetitive loading on soil deformation, two different dynamic approaches were carried out. Initially, following a similar sample preparation as described for the quasi-static approach, dynamic tri-axial compression was intended on the soil treatments S2 as per Table 4.3. First, an ‘in situ’ field stress condition of 250 kPa was set. Then, testing was un-drained and load-controlled using a user-defined waveform (Figure 4.6) to simulate a repeated axial cyclic stress of 2 kN at the maximum peak rate-of-loading of 6.5 kN s^{-1} up to 50 cycles.

If the test is load controlled the equipment requires an estimate of the load stiffness. This is used to set the servo loop gain for load control. If the value chosen is too low, the system would start oscillating. The following trial and error procedure suggested by the equipment designer was followed to work out this estimated value. First, a static cyclic test using the same load and rate-of-loading inputs was carried out. Using this data, an average stiffness value (x, say) was estimated. Afterwards, a dynamic cyclic test with only one or two cycles, using a stiffness of 5x was carried out. Then, the waveform of force against time was examined, if it was poor (not reaching targets or not sinusoidal in shape) then another dynamic cyclic test using a stiffness value of half of the previous value (making the system more responsive) was carried out and the waveform was checked again. The procedure was repeated until the waveform looked appropriate and the load amplitude targets were met for an estimated value of the soil initial stiffness of 1 kN mm^{-1}. To ensure full contact between the soil sample and the equipment, a minimum pre-load of 0.01 kN was maintained between cycles.

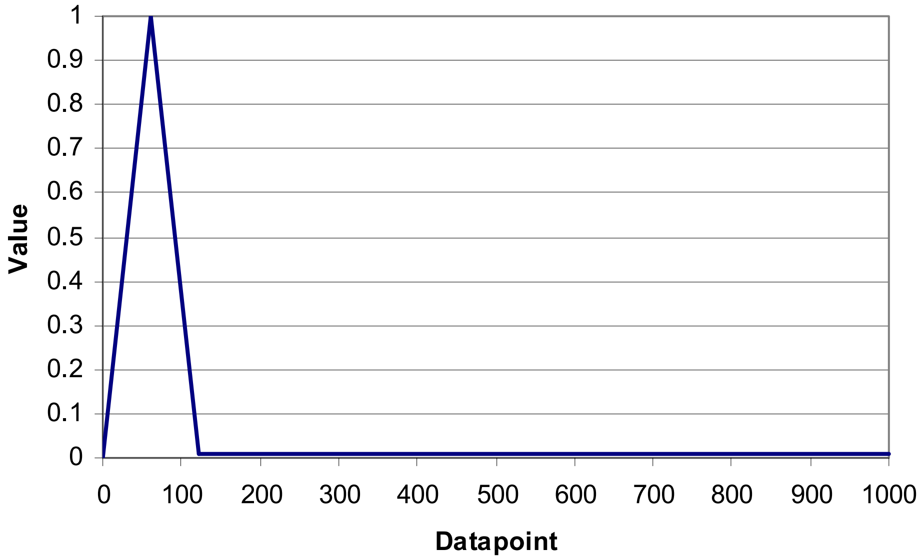


Figure 4.6 User defined waveform to assess the effect of the rate-of-loading on soil stiffness under dynamic compression. The impulse wave was scaled up to 2 kN and run at 2 and 0.2 Hz to achieve 6.5 and 0.65 kN s^{-1}, respectively.

On a second dynamic compression approach the compression system was modified. The soils were confined in a quasi-rigid plastic tube (Ø 115 x 150 length x 5 mm wall thickness) and then mounted between an electromechanical ram and a Ø 70 mm Perspex cap fitted to a 10 kN force transducer.

The plastic container was made to have the biggest size to be safely fitted within the DYNNTS system chamber. This modified approach overcomes the handicap of the water pressure controllers to respond quickly enough to the dynamic load to maintain cell pressure. Moreover, it minimized border effects that could affect soil lateral deformation and removed sample dilation effects that can occur when using compressed water (as with the standard approach). Testing was un-drained and load-controlled using a user-defined waveform (Figure 4.6) to reproduce a repeated axial cyclic stress of 2 kN up to 30 cycles. To test the effect of the loading rate on stiffness, peak rate-of-loadings of 6.5 and 0.65 kN s^{-1} were tested on S2 and C2 treatments. Moreover, to test the effect of moisture on stiffness for the material that was seen to be particularly sensitive to changes in moisture, the Clay Loam, an extra C1 treatment was tested as outlined in Table 4.4. All experiments were replicated three times.

Table 4.4 Sand and Clay Loam treatments used for dynamic testing.

Variable	Sand		Clay loam		
	S2	S2	C2	C2	C1
ρ_b (g cm^{-3})	1.75	1.75	1.60	1.60	1.60
θ_m (%)	11.50	11.50	15.00	15.00	12.00
% Saturation	50	50	50	50	40
dF_z^{max} (BW s^{-1})	6.5	0.65	6.5	0.65	6.5

Radial pressure, water volume, axial force and axial displacement during loading were logged at 100 Hz and converted to stress and strain respectively. The quasi-static and dynamic stiffness moduli and Mohr-Coulomb parameters were calculated in MATLAB from the data recorded. Differences within and between different treatments were determined using ANOVA ($p < 0.05$).

4.3. Results and discussion

4.3.1. Quasi-static tri-axial compression

Stiffness moduli

The results from the ANOVA ($p < 0.05$) performed on the stiffness moduli data derived from the tri-axial compression experiments carried out on the different Sand and Clay Loam treatments presented in Table 4.5 are presented in Table 4.6 and Table 4.7, respectively.

Table 4.6 Elastic moduli in (MN m^{-2}) for the set of Sand states defined in Table 4-2. The subscript index represents confining pressure. S5 treatment represents a grass-rooted condition.

	S1	S2	S3	S4	S5
ρ_b (g cm^{-3})	1.75	1.75	1.75	1.60	1.75
θ_m (%)	6.00	11.50	17.00	11.50	11.50
E	25.70 ± 0.18	31.96 ± 0.11	14.59 ± 0.10	12.87 ± 0.10	6.51 ± 0.11
D_{100}	158.77 ± 2.13	191.58 ± 2.24	121.17 ± 2.75	96.94 ± 2.27	57.47 ± 1.52
D_{300}	298.56 ± 4.53	355.10 ± 4.08	231.73 ± 3.98	205.59 ± 3.82	201.50 ± 3.67
K_{100}	19.20 ± 0.36	25.47 ± 0.25	14.03 ± 0.27	9.86 ± 0.38	5.02 ± 0.34
K_{300}	19.90 ± 0.51	26.60 ± 0.41	14.56 ± 0.20	10.15 ± 0.44	5.10 ± 0.43
G_{100}	16.49 ± 0.11	20.79 ± 0.11	9.72 ± 0.33	8.30 ± 0.32	4.17 ± 0.18
G_{300}	16.40 ± 0.10	20.65 ± 0.10	9.68 ± 0.62	8.26 ± 0.35	4.19 ± 0.23
v_{100}	0.26 ± 0.01	0.29 ± 0.01	0.33 ± 0.01	0.28 ± 0.01	0.28 ± 0.01
v_{300}	0.27 ± 0.01	0.30 ± 0.01	0.33 ± 0.01	0.29 ± 0.01	0.28 ± 0.01

Table 4.7 Elastic moduli in (MN m^{-2}) for the set of Clay Loam states defined in Table 4-2. The subscript index represents confining pressure.

	C1	C2	C3	C4
ρ_b (g cm^{-3})	1.60	1.60	1.60	1.30
θ_m (%)	12.00	15.00	18.00	15.00
E	6.01 ± 0.25	4.56 ± 0.18	2.95 ± 0.15	1.46 ± 0.17
$\mathbf{D_{100}}$	8.42 ± 0.36	6.31 ± 0.23	4.37 ± 0.21	2.15 ± 0.12
$\mathbf{D_{300}}$	9.74 ± 0.31	8.29 ± 0.24	6.93 ± 0.28	4.10 ± 0.19
$\mathbf{K_{100}}$	4.86 ± 0.15	4.87 ± 0.16	3.89 ± 0.12	1.45 ± 0.17
$\mathbf{K_{300}}$	5.03 ± 177.47	4.98 ± 0.20	4.19 ± 0.13	1.47 ± 0.16
$\mathbf{G_{100}}$	3.92 ± 0.10	3.02 ± 0.41	2.04 ± 0.22	1.00 ± 0.15
$\mathbf{G_{300}}$	3.89 ± 0.24	3.07 ± 0.11	2.03 ± 0.18	0.98 ± 0.35
$\mathbf{v_{100}}$	0.29 ± 0.01	0.34 ± 0.01	0.37 ± 0.01	0.33 ± 0.01
$\mathbf{v_{300}}$	0.30 ± 0.01	0.35 ± 0.01	0.38 ± 0.01	0.33 ± 0.01

The Young's modulus (E), the bulk modulus (K) and the shear modulus (G) were found to increase with the applied confining pressure and mean normal stress for both soils. This was caused by the decrease in soil specific volume (Figure 4.7) and so the increase in dry bulk density that takes place as a result of the shrinkage caused by the increase in the isotropic confining pressure. Little variation was found for the Poisson's ratio, which remained relatively unchanged. Some hysteresis (or energy loss) occurred during the process. It was noticed that a compressed sample, once the confining stress was released, did not totally recover its original size. This revealed that sample was subjected to elastic but also plastic deformation during the isotropic process. An initial elastic response takes places, then air pores are compressed and partially removed (into solution) and the material is compacted.

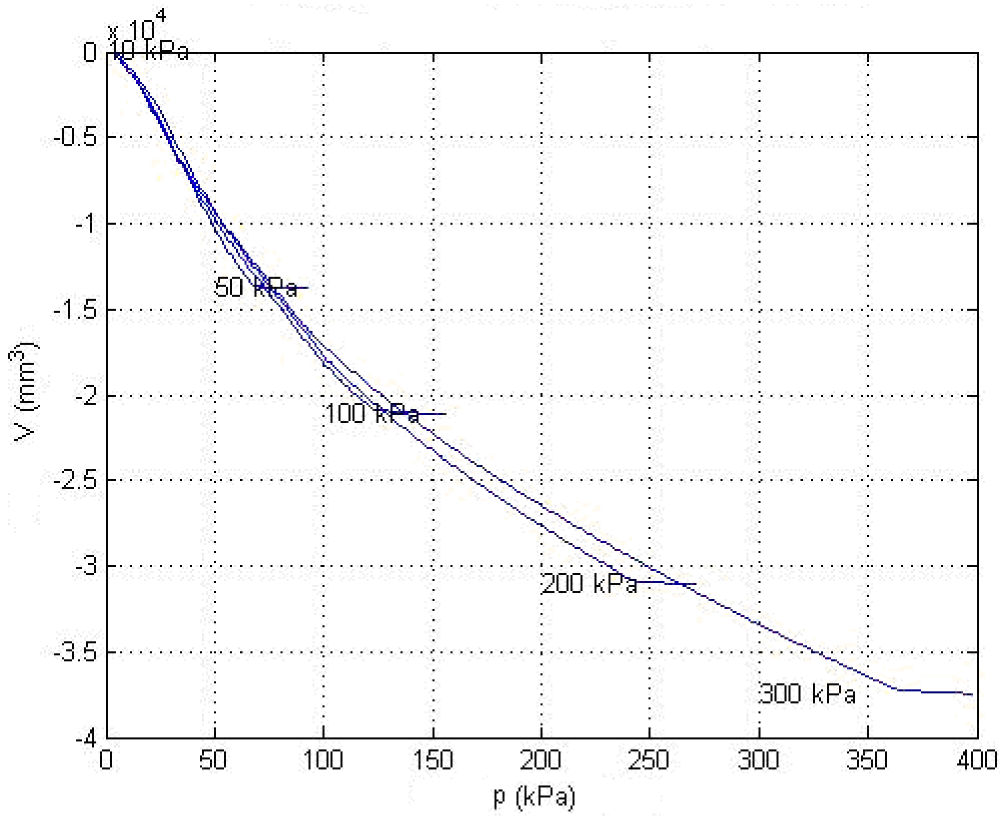


Figure 4.7 Isotropic compression lines for the S2 treatment. The soil compresses and becomes more dense, and therefore stiffer, so that the specific-volume / stress line is curved and getting less steep.

Different patterns were found between soils when assessing the effect of moisture in the stiffness moduli, keeping a constant initial dry bulk density. For the Sand treatments, the moduli initially increased significantly with the increase of moisture (S1 < S2) to finally decrease at greater moisture contents (S3 < S1 < S2). Following the discussion presented in Section 3.4.1, increasing water content increases the water tension between the pores of the soil due to adhesive (solid-water) and cohesive (water-water) forces holding the particles together and so increases soil strength, up to a point where too much water will bring particles apart and so decreasing soil strength again. For the Clay Loam, the moduli decreased significantly with moisture in a progressive way (C3 < C2 < C1), because the bonds that hold the particles together are weakened as more water is absorbed between adjacent clay minerals.

For both soils, at a constant moisture content, the stiffness moduli decreased significantly with a decrease in the initial dry bulk density (S4 < S2 and C4 < C2) as a result of less friction developed between adjacent particles. Poisson's ratio increased with initial dry bulk density and moisture content because the material is less compressible and allows axial stress to be more easily transmitted transversally. In general and for the treatments tested, the stiffness of the Sand was greater than the Clay Loam which is in good agreement with other data in the literature (Kulhawy and Mayne, 1990) and also reinforces the idea that was suggested in Chapter 3 that the intrinsic stiffness of the Sand is greater than Clay Loam condition.

Significantly lower stiffness moduli were measured for the grass-rooted treatment (S5) compared to the bare soil (S2). If a material with high strength in tension, such as grass roots, is placed in soil, then the reinforced composite material could be expected to resist bending and other tensile actions created by players, such as a reduction in horizontal strain (Shipton, 2008). In this sense, grass roots system can be seen as a moment resisting reinforcement for soil. However, the inclusion of these relatively elastic elements (grass roots) can be expected to cause a reduction in the vertical composite stiffness (Zheng-Yi and Sutter, 2000*)*. As typically found for fibre-reinforced plastic, the load in compression can make the fibres become loose gradually as the soil is compressed, especially at low confining pressures. The heterogeneity discovered in the root system developed (Figure 4.5) and the impossibility to achieve a smooth surface free of grass that could motivate an early failure during compression testing due to an inappropriate setting of the sample on the tri-axial platform could also contribute to the lower stiffness found out for the rooted samples. Due to these uncertainties and that it represents a very time-consuming process the approach of testing grass-roots samples was not performed on any Clay Loam treatment.

Mohr-Coulomb models

The results from the ANOVA ($p < 0.05$) performed on the deviator stress data obtained from tri-axial compression testing and the subsequent Mohr-Coulomb parameters worked out for the different Sand and Clay Loam treatments tested are presented in Table 4.8 and Table 4.9, respectively.

Table 4.8 Mohr-Coulomb parameters in ($kN\ m^{-2}$) for the set of treatments defined in Table 4-2.

	S1	S2	S3	S4	S5
ρ_b ($g\ cm^{-3}$)	1.75	1.75	1.75	1.60	1.75
θ_m (%)	6.00	11.50	17.00	11.50	11.50
q_1^{max}	63.24 ± 3.82	72.79 ± 3.51	57.64 ± 4.13	22.56 ± 3.04	69.62 ± 6.65
q_{100}^{max}	262.04 ± 16.01	283.84 ± 14.81	221.74 ± 16.36	173.40 ± 13.27	272.85 ± 12.95
q_{300}^{max}	658.51 ± 28.73	687.87 ± 29.53	615.16 ± 28.15	503.85 ± 26.60	680.55 ± 26.26
c	17.92 ± 0.92	21.12 ± 0.76	13.15 ± 0.68	5.34 ± 0.89	21.87 ± 1.62
ϕ (°)	27.91 ± 0.29	31.81 ± 0.24	3.79 ± 0.33	26.54 ± 0.27	29.35 ± 0.18

Table 4.9 Mohr-Coulomb parameters in ($kN\ m^{-2}$) for the set of treatments defined in Table 4-2.

	C1	C2	C3	C4
ρ_b ($g\ cm^{-3}$)	1.60	1.60	1.60	1.30
θ_m (%)	12.00	15.00	18.00	15.00
q_1^{max}	100.86 ± 6.27	77.96 ± 1.69	53.60 ± 3.64	24.85 ± 1.63
q_{100}^{max}	176.89 ± 17.44	155.54 ± 13.45	84.43 ± 13.07	60.83 ± 12.91
q_{300}^{max}	443.38 ± 28.43	226.34 ± 29.06	107.22 ± 24.52	114.38 ± 23.19
c	39.79 ± 1.02	35.71 ± 1.04	26.43 ± 1.51	11.64 ± 0.11
ϕ (°)	17.54 ± 0.34	11.53 ± 0.32	4.92 ± 0.40	7.45 ± 0.23

The experiments showed that regardless of the soil, the deviator stress (q) at first increases quickly while the strain increases slowly, but as the soil yields the strain increases dramatically while the stress difference levels off and then begins to fall (Figure 4.8). It was observed that changes in the applied mean normal stress have a remarkable effect on the strength of soils, resulting in greater peak stresses (q_{max}) with increased confining stress. Moreover, materials with higher confinement were stiffer at smaller values of strain, and as the confining stress was increased, the curvature of the deviator stress decreased and its maximum strength (q_{max}) occurred, on average, at a greater level of axial deformation. This is because as the surrounding stress is increased the material gets more compressed, increasing the contact area and the friction between the particles within the sample leading to a greater final macroscopic soil strength.

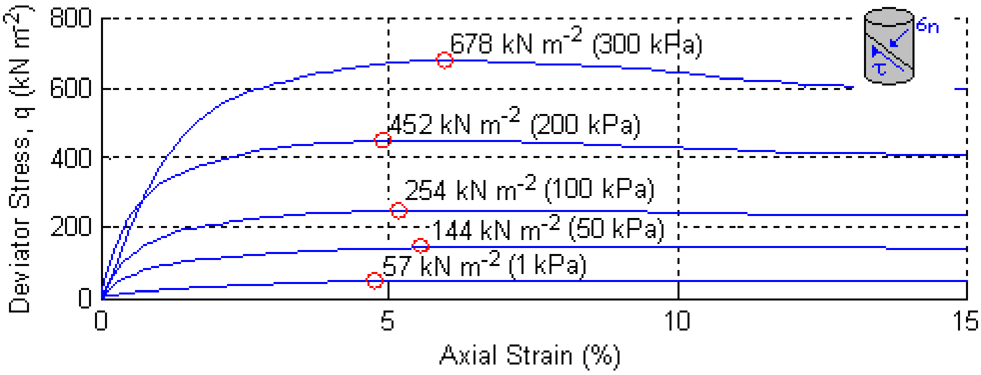


Figure 4.8 Typical quasi-static axial stress-strain behaviour of S2 treatment after tri-axial shear failure at five different confining pressures. Plastic yield points (q_{max}) marked in red.

A different trend was found between the two soils when assessing the effect of moisture on the peak stress and Mohr-Coulomb parameters. For the Sand, peak stress initially increased significantly with the increase of moisture (S1 < S2) until finally decreasing (S3 < S1 < S2) when water lubricates in excess and separates the adjacent particles. For the Clay Loam no initial increase was found instead a steady decrease in the strength parameters was measured with increasing moisture content (C3 < C2 < C1).

A decrease in the initial dry bulk density caused lower strength parameters (S4 < S2 and C4 < C2) as a result of less internal frictional resistance developed between adjacent grains. This is clear evidence that shear strength is strongly dependent on dry bulk density and moisture content, especially for the Clay Loam treatments where the difference in angle of friction was more acute.

Greater axial deformations at the time of peak stress were measured for the grass-rooted samples (S5) compared to the bare soil treatment at a constant moisture and initial dry bulk density (S2). This may suggest that the integrity of the system is maintained for longer when a root reinforcing system is present. However, significantly lower values of c and ϕ were measured for the grass-rooted treatment which, again, is suggested to be due to method limitations explained in the previous section rather than a real trend. The literature has shown that a well root-permeated soil will cause an increase in shear strength (Jennings-Temple, 2005).

Samples were observed to fail in either a compressive or brittle manner (Figure 4.9) which was related to two different soil behaviours: strain hardening or softening. Compressive failure was considered to have occurred when the deviator stress remained constant at the maximum value and brittle failure when the curve showed a decline from the maximum. Strain hardening was the general rule observed along the experiments and was especially noticeable at low confining stresses (1 kPa) and low initial dry bulk density (S4 and C4). The disturbance during shearing causes the grains to move closer together, especially with loosely packed grains (low densities and confining pressures), implying an increase in soil density during the deformation process and failure occurrence along an infinite number of planes (Godwin and Spoor, 1977). Strain softening was observed for some of the treatments submitted to higher confining pressures (300 kPa). In this case, the disturbance during shearing forced highly packed particles in one layer to climb over the particles in the underlying layer, distorting the boundary of the soil sample and causing dilation. As a consequence, brittle failure occurs along a few well defined failure planes, the rest of the soil tends to move as solid blocks. A transition from compressive to brittle failure as the cell pressure was increased can therefore be suggested from the discussion above.

Figure 4.9 Compressive (left) and brittle (right) failure following quasi-static tri-axial compression testing.

As an illustrative example, the average Mohr-Coulomb strength linear model for the S2 treatment is presented next following Equation 4.17.

$$\tau = 0.62\sigma + 21.12 \qquad \text{(Equation 4.31)}$$

Where the cohesion is 21.12 kPa and the angle of internal friction is 31.81˚ as shown in Table 4.8. The failure criterion allows predicting the maximum axial stress that can be applied before the material fails in shear. This can be described as a particular limiting condition of the ratio between shear and normal stress:

$$\frac{\tau - 21.12}{\sigma} \leq \tan 31.81^{\circ} \qquad \text{(Equation 4.32)}$$

Where τ is the un-drained total shear strength, that is, the is the maximum stress that can be applied tangentially on a plane within a soil before sliding occurs on that plane at angle of approximately 60º (Figure 4.9) as per Equation 4.18; σ is the stress normal to the shear plane; and tan ϕ is the slope of the corresponding Mohr-Coulomb failure strength envelope (Figure 4.10). Points below the envelope represent stress ratios possible prior to yielding, whereas points on the envelope represent the stress ratio at yielding. Real points above the envelope cannot exist.

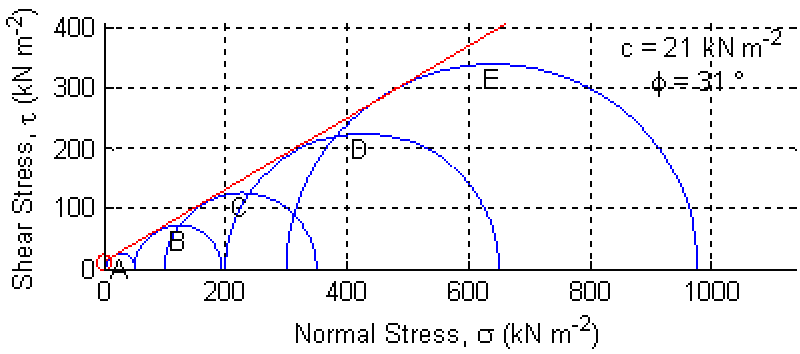


Figure 4.10 Mean Mohr-Coulomb stress failure envelope for peak stress (q_{max}) obtained for S2 treatment. The red line represents the best straight line through the plot points.

The main disadvantage of the Coulomb's equation is that it ignores volume changes. Loading of an unsaturated soil does induce changes in its volume that will make soil denser, moving the particles closer together and increasing the friction and interlocking between them and therefore making the soil stiffer, which will modify the final shear strength. However, the major limitation in relation to this Mohr-Coulomb modelling approach in this study is that the model makes no statement about rate of strain. The quasi-static approach, although very time consuming, was found to be useful for comparing basic mechanical properties for different soil treatments. It was hypothesized that soil mechanical properties will change if the strain rate is increased from a typical quasi-static compression test run at 5 x 10^{-4} kN s^{-1} to a typical sport movement performed at 70-80 kN s^{-1}. Therefore, an alternative methodology to the Mohr-Coulomb strength models for predicting the stress-strain dynamic behaviour of soils is necessary.

4.3.2. Dynamic tri-axial compression

When a cyclic loading was imposed during standard tri-axial compression (using pressurized water), a confining pressure drop of around 40 kPa occurred in the chamber at the start of the loading process (Figure 4.11). As a consequence, it took a large number of cycles for the system to reach the initial confining pressure target (250 kPa).

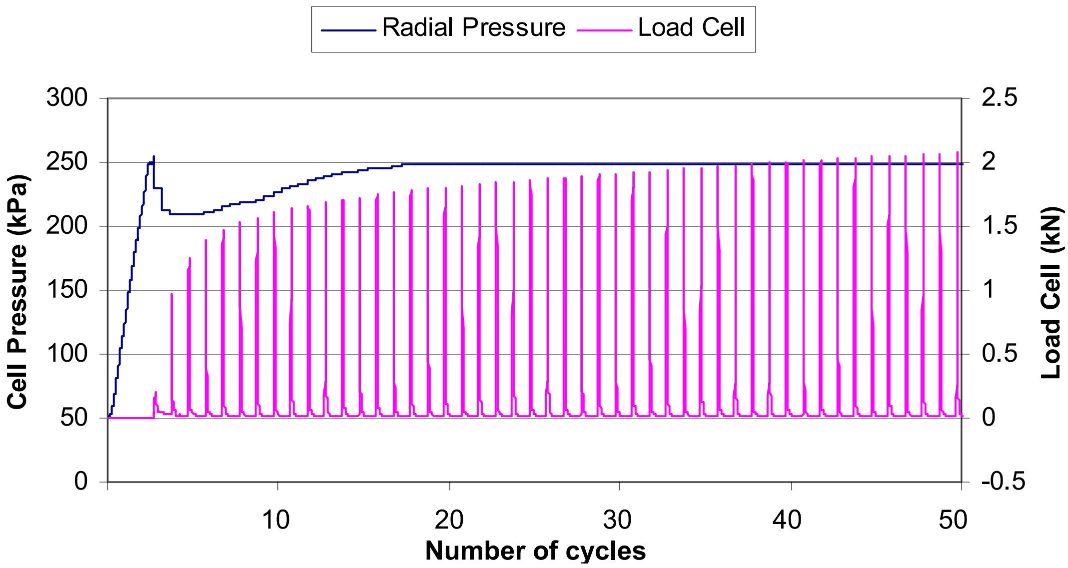


Figure 4.11 Cell pressure drops at the beginning of the axial compression stage. The control system does not meet the 2kN target for the first few cycle. The cell pressure dropped around 40 kPa and the variation in maximum axial stress was around 75 %.

It is believed that the pressure drop was caused by the great change in soil stiffness when the first load was applied. Soil stiffness changes every cycle as the sample gets more and more compacted, but the magnitude of change is particularly significant during the first cycles when the soil can undergo more compaction. The DYNNTS is provided with a balanced ram that compensates for the volumetric displacement of the thrust piston into or out of the water cell. The control system could not react by pumping water quickly enough into the tri-axial cell to counteract sample compaction and so pressure dropped. This drop caused a decrease in soil stiffness, the more compacted the sample gets, the less water is needed to be pumped into the system to counteract the decrease in cell pressure created by that compaction and the process becomes a vicious cycle until suddenly a break-even point is reached, where the stiffness change is small enough to be compensated by the apparatus.

A control software limitation was found when trying to select a delay time between cycles. The current control system does not allow the user to do that, which means that running at 2 Hz, the load is applied over less than 0.1 s and the only delay between cycles is about 0.40 s, which raises the question of whether or not that is enough time for the soil to recover fully from the previous loading. Another difficulty was found in that the un-saturated samples were initially less stiff than the minimum stiffness estimated value that could be selected at the frequency tested (1 kN mm^{-1}). Despite the fact that parameter is frequency dependent, it was simply input into the control system as a constant value which was not accurate enough to properly control the process.

It is acknowledged that the current equipment has been used to do tests for which it was not originally designed. The DYNNTS system may be satisfactory when dealing with saturated soils, where the change in stiffness will be a lot smaller, but it was not when dealing with un-saturated soils and the load range required for this study. As a consequence, not only did this change the cell pressure but also the shape of the load waveform and the load target were massively altered (Figure 4.11). The load applied within the first few cycles was around 75 % smaller than for the following cycles at the target stress level. For the cycles that the target stress is not reached the energy accumulated in the soil will be also proportionally less than for the rest of the cycles. Soil deformation was required to be produced within fixed stress boundary conditions that ensured a constant level of impact energy and so a proper reproduction of a running movement.

It was also difficult to select the correct value for the confining pressure to be used. This value was calculated based on calculations for saturated foundations and will probably differ from an in-situ measurement on an NTP. It is thought that the selected value overestimates the lateral in-situ pressure. Lower confining pressures were unsuccessfully tested, because the change in soil stiffness was greater and the dynamic maximum amplitude limit of the equipment was exceeded. The amplitude and frequency are interdependent. If one is increased, the other one is decreased and vice versa. Under dynamic loading, as frequency increases, more and more torque is required to accelerate and decelerate the drive system. This means that less torque is available for axial force and so axial force capacity reduces. When dealing with frequencies of about 1-2 Hz, as is the case here, the performance of the system is limited by the maximum velocity or speed of the motor. The maximum amplitude is inversely proportional to frequency and is, according to the tri-axial device supplier about 5 mm at 2 Hz. This amplitude limitation can be added on to the above explanation of why the load targets could not be met. If for the first cycles, where the soil is found at its weakest condition, the velocity needed to achieve the load is not sufficient and the system needs to deform the sample more than the maximum amplitude limit allowed, then the load targets will not be reached. The motor in the DYNNTS system was found to be insufficiently powerful to be able to achieve the speeds required.

However, even if the right rate of loading could be achieved, the water used to confine the sample in the tri-axial method would not be able to transmit the shear stresses that the surrounding soil would do in the field under dynamic loading. This would make a running simulation difficult to justify via standard tri-axial compression testing. Moreover, the fact that the soil is isotropically pressurized implies that a positive pore pressure is developed in the sample, which is not usually the case in the field near the surface, where water is retained under a negative pore pressure. It is also unknown how the membrane will affect the measurement of dynamic properties, and no correction was found in the literature for dynamic testing. With consideration of all the above limitations, it was concluded that the standard method generates a lot of unknowns that reduce confidence in the robustness of dynamic, high loading rate, tri-axial compression testing for assessing NTPs in this project.

4.3.3. Dynamic uni-axial compression

Figure 4.12 illustrates the non-linear visco-plastic stress-strain behaviour typically exhibited by the soil treatments tested using the modified uni-axial method described in Section 4.2.5. After a cycle, the system absorbed the energy represented by the area enclosed by the loading and unloading curves in the cycle (Figure 4.12) and accumulated a certain amount of permanent strain. After the loading, however, there was also a certain elastic strain accumulated, that was recovered in the unloading but only to a limited extent.

For the initial cycles, plastic behaviour dominates as the soil is compacted. Subsequently over cycles more strain is recovered and less plastic strain is accumulated, therefore the response becomes more elastic. As the soil gets more and more compacted, its microstructure changes, particles get closer together increasing their frictional contacts resulting in a macroscopic increase in stiffness. Reversible elastic strain in soils is associated with minimal rearrangement of particle contacts and is relatively limited when dealing with traditional strain rates (as was presented in Section 4.3.1). However elastic strain becomes more significant at high strain rate levels. Regardless of the treatment, after about 30 cycles it was assumed that no real further compaction took place and that a nearly elastic response was obtained.

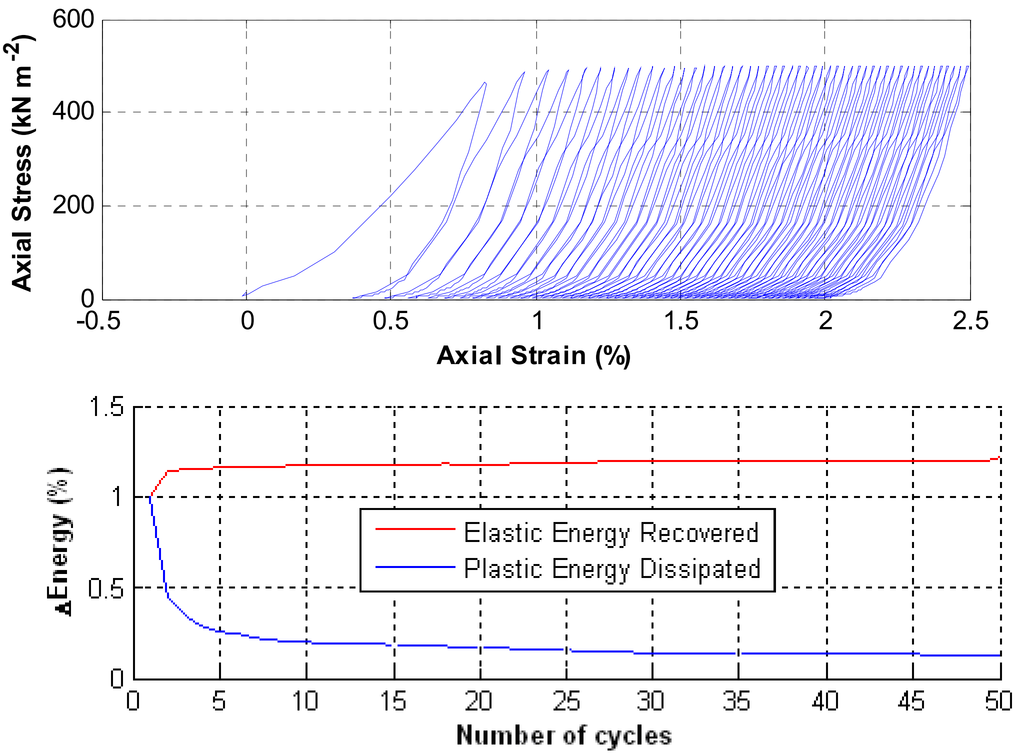


Figure 4.12 Non-linear visco-plastic stress-strain soil behaviour: cyclical stress loops (upper). The S2 treatment was loaded up to 2 kN at 6.5 kN s^{-1} for 50 cycles. The variation in maximum axial stress remained below 10%. The deformation energy balance (lower) shows that reversible elastic behaviour became more significant at high strain levels and, plastic deformation decreased over cycles. The recovery process takes time causing a viscous behaviour.

This modified approach overcame some of the main problems found with the standard tri-axial approach: a target level of stress around 500 kPa was maintained consistently over the 30 cycles. The load applied within the first few cycles was only around 10 % smaller than for the following cycles. Again, it is believed that this variation was due to the changing stiffness of the soil as it was loaded repeatedly. It was considered that the stress applied exceeded the strength of the material and therefore shear failure should have occurred producing irrecoverable plastic strains as shown in Figure 4.12. Soil displacement was accompanied over cycles by lifting of the ground surface adjacent to the footing which made it difficult to work with a large number of cycles. Traditionally, when a pile is driven into a homogeneous soil mass, the supporting ground is expected to fail in shear during loading along a log-spiral (Whitlow, 2001). If this theory may be applicable to the present case, a shear failure taking place with slip surfaces extending on a log-spiral from the side edges of the footing downward through the soil and then upward to the ground surface (Figure 4.13) could be suggested as the failure mechanism.

Figure 4.13 In the modified dynamic compression approach (upper) soils were confined in a quasi-rigid plastic tube, mounted between an electromechanical ram beneath and a plastic cap fitted to a force transducer and subjected to a cyclic dynamic normal stress (σ_a). Suggested log-spiral failure mechanism sketch (lower).

The steady-state dynamic stiffnesses, k_d^{max} achieved are detailed in Table 4.10. Dynamic stiffness was greater at the greater rates of loading for all the treatments ($p < 0.05$). Moreover, overall dynamic stiffness was significantly greater for the Sand soil than for the Clay Loam soil ($p < 0.001$). The Clay Loam treatment with lower moisture content also significantly increased the stiffness with respect to the dry clay soil ($p < 0.001$). This is due to increased friction within the drier clay soil as moisture content decreases, as discussed for the quasi-static testing in previous sections.

The faster the soil is deformed, the less it will be compressed because the time for the normal deformation mechanisms to occur reduces – this confirms the hypothesis stated above. The results highlight the importance of the elastic-plastic behaviour of soils (or the soil-turf matrix) and the difference in dynamic mechanical behaviour between soil types. Soil yield intensity has been cited to be related to the strain rate; soil volume change decreases and soil strength increases with increasing strain rates (Vucetic and Dobry, 1991; Horn, 2004). Traditional quasi-static soil testing such as tri-axial compression testing, involves very low strain rates that allow enough time for the soil to deform through irreversible fracture mechanisms that imply large amounts of plastic deformation (Fredlund et al., 1997). However, as the stress is applied more quickly to the soil, the time to deform reduces and the overall soil strength increases as a result.

Table 4.10 Mean steady-state dynamic stiffness k_d^{max} and standard error for the soil treatments tested. All means separated by the LSD (0.05)

Treatment	ρ_b (g cm^3)	θ_m (%)	dF_z^{max} (kN s^{-1})	k_d^{max} (MN m^{-2})
S2	1.75	11.5	0.65	58.1 ± 0.9
S2	1.75	11.5	6.5	84.4 ± 0.9
C2	1.6	15	0.65	25.3 ± 0.2
C2	1.6	15	6.5	33.5 ± 0.2
C1	1.6	12	6.5	50.5 ± 0.2

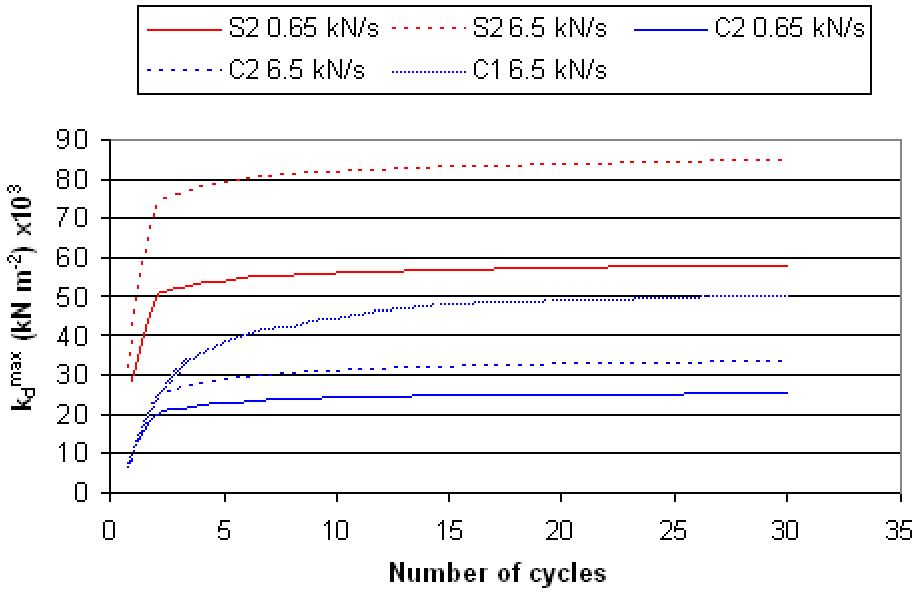


Figure 4.14 Change in mean dynamic stiffness with increasing cyclic loading. The effect of loading rate and soil type on stiffness is evident.

4.4. *Soil Mechanical study summary and evaluation*

A quasi-static tri-axial compression approach was performed on several different treatments using the Sand and Clay Loam materials used for the biomechanical study described in Chapter 3. This enabled evaluation of the effect of moisture, density and grass rooting on the elastic moduli and the shear strength of the materials. In general, the values of the mechanical parameters of both soils increased with increasing the bulk density. The Sand material presented more elastic behaviour than the Clay Loam material for the range of density and moisture content conditions tested. The Clay Loam presented a more acute change in mechanical properties with moisture content. Quasi-static stiffness of the Sand soil followed a negative-quadratic model shape behaviour with moisture, presenting the maximum stiffness at an optimum moisture content. The Mohr-Coulomb strength analysis revealed greater frictional and cohesive components for the Sand and Clay Loam material, respectively as would be hypothesised for these soil types. The effect of grass rooting was not clearly determined due to approach limitations and alternative methods to tri-axial compression such as the use of a penetrometer are suggested for further research (Jennings-Temple, 2005).

A modified uni-axial dynamic compression approach was found to provide more reliable results than standard dynamic tri-axial compression. Thus, it allowed evaluation of the dynamic stiffness evolution of the soil materials involved in the project as a function of the rate-of-loading. Sands were found to be stiffer than clay soils in this study (again, subject to the range of conditions tested). This has direct performance implications in elite winter sporting surfaces which are increasingly sand based. It also explains the difference found in biomechanical loading. It was discovered in Chapter 3 that loading rate of a soil by a player running in the biomechanics laboratory was significantly greater on the Sand soil than the Clay Loam soil.

At the time of this study, it was not possible to locate equipment in the UK to perform at the 20 Hz frequencies required to carry out such tests. The trend of increased dynamic stiffness as loading rate was increased from 1/100 to 1/10 of the loading rate determined in the running experiments confirmed the hypothesis that the stiffness of the Sand soil was significantly greater than the Clay Loam soil, however. The closer the loads used to test mechanical properties of the surfaces in the lab are to those performed by the player, the better the understanding will be on how an NTP will behave in response to player action. It is therefore, recommended that further research characterizes soil dynamic behaviour at the closest possible stress-strain rates that they will be subjected to in real sport.

The data presented are of direct significance in the understanding of human-surface interactions. Historically, studies of NTPs have been concerned with the plastic deformation of soils, using parameters such as ‘wear and tear’. In order to understand the impact loads on the body and surface, however, it is essential to study and model dynamic behaviour. It is this that reveals the elastic stiffness of a surface when loading within the range of those loads applied by humans in sport. The plastic component of soils, or the soil-turf matrix, increases the contact time between the human and the surface (or the ball and the surface), reducing the peak impact loads on the body (or moderating ball rebound behaviour). The elastic component is essential for energy return to the player (or ball) and for resilience or recovery of the grass-soil matrix material and it is proposed to test the grass-soil matrix as it is presented in the real sport field. A high sand content surface, unlike a high clay content surface, will present a higher intrinsic stiffness that will imply an increased elastic behaviour and that will benefit sport performance. In turn, a reduced plastic deformation could imply greater peak load being transferred to the players and so it may imply a greater risk of injury for them. Therefore, the present study furthers the understanding of how visco-plastic soil behaviour affects the player-surface interaction in sport.

5. RELATIONSHIP BETWEEN THE BIOMECHANICAL AND SOIL MECHANICAL STUDY AND RESEARCH SYNTHESIS

5.1. Introduction

The analysis carried out so far demonstrates that the interaction between player and a natural turf surface is complex. The human body responds to changes in surface condition by changing its way of running. The surface, in turn, deforms under load from the player but as the surface deforms and its mechanical properties change, there is a change in the applied stress from the player. The present chapter links the player biomechanical behaviour observed in Chapter 3 with the surface mechanical behaviour discovered in Chapter 4 into a conceptual model (Objective 4). The whole project approach is evaluated and some recommendations for future research proposed together with a summary of the publications derived from the present study.

5.2. Conceptual model

On the one hand, highly impact cushioning or low stiffness surfaces will yield to the player, reducing physiological stress but increasing the energy consumption of the player and so fatigue due to a greater compressibility of the surface. At the same time, compliant or low stiffness surfaces will present a higher risk of compaction and unevenness, creating an undesirable low oxygen condition for the grass plant and increasing surface wear. A stiff surface, in turn, may increase physiological stress to the human but will result in more efficient energy balance due to a limited surface deformation. At the same time, greater stiffness implies less surface compaction and so a more homogenous and even surface.

On the other hand, low surface shear strength will cause player instability due to the lack of traction, with the consequent risk of injury for the player. A low strength surface will be more susceptible to wear and degradation. Excessive shear strength will imply little deformation of the surface and will cause too much traction with the subsequent higher risk of injury for the player.

An optimum state should exist in between such surface stiffness and shear strength extreme conditions where injury risk and surface wear would be kept at a minimum level while allowing for a reasonable level of sport performance. This is conceptualized in Figure 5.1.

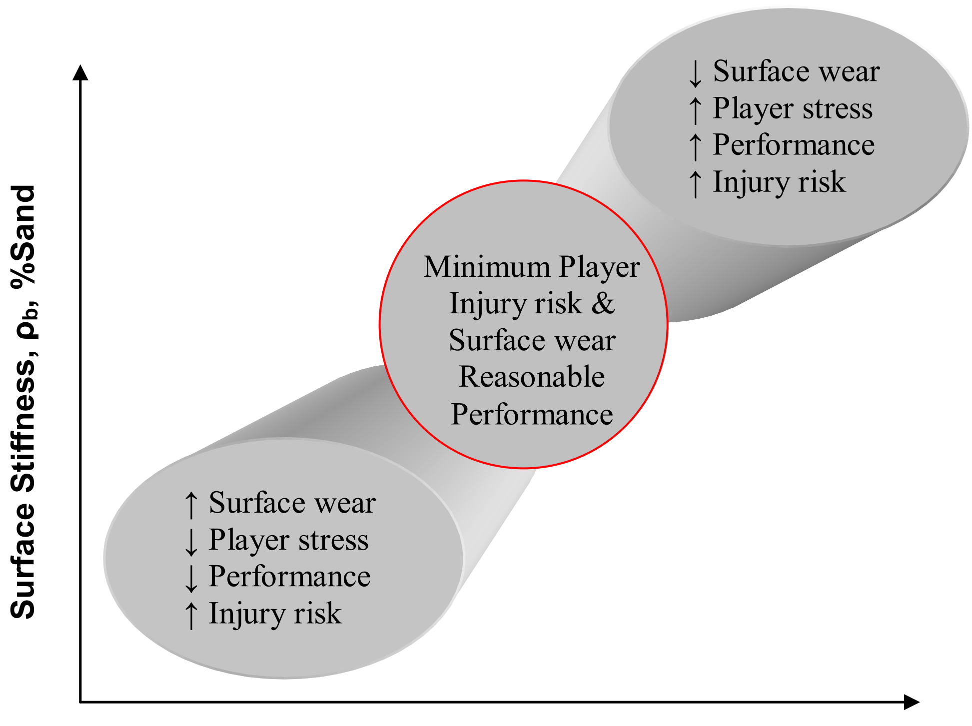


Figure 5.1 Conceptual model diagram. Stiffness and shear strength are the mechanical properties that determine the surface impact cushioning and traction, respectively. Player stress it is the stress on the player as a consequence of interaction with the surface. Generally, a decrease in moisture content would cause and increase in surface stiffness and shear strength, although as the percentage of sand is increased, there is minimum amount of water below which those properties decrease.

Kinetic biomechanics evidence was found to support the hypothesis that it is the surface that controls player rate of loading when running. The peak vertical rate-of-loading (dF_z^{max}) and the peak pressure rate-of-loading (dP^{max}) increase as the stiffness of the surface increases, as a result of a reduction in surface deformation. Subgroup A player, dF_z^{max} increased from 125.05 ± 6.49 to 153.17 ± 7.17 BW s^{-1} and dP^{max} increased from 0.61 ± 0.06 to 0.78 ± 0.06 BW mm^{-2} s^{-1} when changing from a clay-based to a sand-based surface condition. This rate increment allows for the energy to be transmitted more quickly from the player to the surface and then back to player again.

Soil mechanics evidence was found to support the hypothesis that the level of compaction and the stiffness of the surface are controlled by player-applied stress. Surface stiffness increases as the surface is compacted from player-applied loads. The Clegg Hammer showed that the stiffness of the surface was greater in general for a compacted surface after player testing and that the magnitude of the difference in stiffness depends on the surface type. Hardness increased from 58.56 ± 2.93 to 63.12 ± 2.73 G and from 60.64 ± 3.58 to 71.21 ± 4.98 G for the sand-based and clay-based pitches, respectively. The steady-state dynamic stiffnesses (k_d^{max}) increases non-linearly with the number of player impacts and the loading rate of the surface, again differently depending on the surface type: k_d^{max} increased from 58.1 ± 0.9 to 84.4 ± 0.9 MN m^{-2} and from 25.3 ± 0.2 to 33.5 ± 0.2 MN m^{-2} for the sand-based and clay-based pitches, respectively, when the loading rate was increased from 0.65 to 6.5 kN s^{-1}. The increase in dynamic stiffness with loading rate is because the faster the soil is loaded the less it is deformed as the time for the deformation to occur reduces. For running, the amount of time that the surface is allowed for deformation is about a quarter of a second. In such a small lapse the capacity for internal particles rearrangement within the soil becomes limited as the usual soil deformation mechanisms require longer times to take place. The greatest the loading rate, the lowest the time for surface deformation and the more restricted the movement within the soil which makes soil skeleton to become stronger, increasing surface stiffness.

The set of soil dynamic compression energy loops presented in Figure 4.12 show that for a constant amount of player energy, the energy dissipated by the surface in plastic deformation is reduced as the soil is compacted. As the surface compacts it becomes stiffer and starts behaving more elastically, returning more energy to the player. For surfaces of the type tested in this study (primarily for soccer) a sand-based surface, unlike a clay-based surface will present a higher intrinsic stiffness that will imply an increased elastic behaviour and that will benefit sport performance. The elastic-plastic mechanical behaviour of NTPs depends on the raw soil material that they are constructed from but also on the turf plant and moisture content at which the surface is maintained. The plastic component of soils, or the soil-turf matrix, represent a necessary loss of energy that increases the contact time between the human and the surface (or the ball and the surface), reducing the peak impact loads on the body (or moderating ball rebound behaviour). The elastic component is essential for energy return to the player (or ball) and for resilience or recovery of the grass-soil matrix material. This has direct performance implications in elite sporting surfaces which are increasingly sand based.

The elastic and plastic hybrid behaviour of NTPs demonstrated in this project links to what Kolitus (2003) stated – that performance aspects of sports are always compromised by safety aspects of the player (and grass plant). Performance can be increased if the loss of energy is minimized and the energy return is maximized and returned at the right location, at the right time and with the right frequency (McMahon and Greene, 1984; Stefanyshyn, 2001). The present study highlights that it is as important to increase the elastic component of the surface, to increase energy return and reduce energy losses as it is to ensure some plastic deformation. Player physiological stress is related to the amount of plastic deformation experienced by the surface and so this could be seen as a necessary energy loss to increase safety.

The findings from the present project support the differences in player comfort levels observed by other researchers such as Nigg et al. (1988a) when investigating the deformation of different surfaces. They observed that stiffer (or less deformable) surfaces were the least comfortable, although the most stable to perform the sport movements, compared to more deformable surfaces. Stiffer surfaces were associated with larger forces acting on the body which were suggested by Fiolkowski and Baur (1997) as a possible cause of overloading injuries. Compressible surfaces increase player energy cost (Lejeune et al., 1998) which may cause of fatigue injury (Millet et al., 2006).

The soil stiffness relationship discovered also explains the biomechanical findings that showed a greater player loading rate for a sand-based pitch compared to a clay-based pitch. In turn, a reduced plastic deformation could imply greater peak load being transferred to the players and so it may imply a greater risk of injury for them. For example, if a collision between player head and surface is considered, the stiffness or compressibility of the surface determines the shock attenuation which is a decisive factor when investigating the risk of potential brain injury (Shorten & Himmelsbach, 2002). As an NTP is loaded, it becomes stiffer (less compressible) and so more likely to produce higher impact accelerations (g_{max}) to absorb the energy involved in a head fall, which may increase head injury risk.

The conceptual model proposed is supported by the biomechanical and mechanical findings of the present research, which are also consistent with existing literature. Therefore, the present study furthers the understanding of how visco-plastic soil behaviour affects the player-surface interaction in sport.

Some authors have suggested several kinematic adaptations with the change in surface cushioning properties of for example, STPs (Dixon & Stiles, 2000; Ferris et al. 1998; 1999; Kerdok et al., 2002). However, in the present study there was no kinematic evidence that different players modified their running behaviour based on the surface they performed on. Therefore the present model described does not present any changes in player stiffness depending on surface. This suggests that either players prefer to maintain similar leg geometries and stiffness when running on a variety of NTPs which would leave the differences in loading rates found unexplained, or alternatively that the mechanical properties of the NTPs selected for the research may not have been sufficiently different to elicit changes in player response during running despite the difference in magnitude of dynamic stiffness determined.

Young's modulus for sand-based pitches was found to be between 6 and 32 MN m^{-2}, whereas for clay-based pitches was between 1 and 6 MN m^{-2} which are values of the same order of magnitude as styrene butadiene rubber (SBR) materials typically used to construct polymeric running tracks but still well bellow concrete stiffness under compression (40 x 10^3 MN m^{-2}). This shows that the magnitude of the difference between the conditions tested for this present study was much smaller compared to the difference between running on a polymeric track or on concrete. This lack of difference in the surface mechanical properties is hypothesise that is suggested to be behind the lack of kinematic adaptations evidence found in this study.

The conceptual model described above presents dry bulk density and moisture content as important parameters affecting surface stiffness and shear strength depending on surface type. An increase in initial dry bulk density increases the initial stiffness and shear strength of the surface as a result of more internal frictional resistance developed between adjacent grains within soil due to greater surface area contact. Moreover, pressure is distributed within an unsaturated soil through the particle-particle contact. A greater dry bulk density implies a lower void ratio (i.e. a larger volume of solids to voids) and will distribute pressure to a greater extent (both down a soil profile and laterally across the soil profile) because of the close arrangement of particles. This way, player energy will be transferred to a larger soil mass that will be more likely to resist against player loading and so increasing surface stiffness and shear strength.

Traction increases in the same way that cushioning decreases as a surface is compacted, up to a point where the surface becomes too hard to be penetrated by boot studs and so the traction actually decreases. Such properties are more sensitive to changes in moisture in clay-based surfaces due to an intrinsically predominant cohesive behaviour. Stiffness and shear strength of clay decreases with increasing moisture content because the internal bonds that hold the particles together in structural units are weakened as more water is absorbed. This water penetrates between adjacent clay minerals hydrating cations and allowing them to swell (and subsequently shrink on drying). Sand-based surfaces, in turn, present an intrinsic greater frictional behaviour where stiffness and shear strength follow a negative-quadratic form of behaviour, with moisture presenting a maximum stiffness at an optimum moisture content due to increased cohesion at that optimum moisture content. For increasing sand content (or strictly, decreasing clay content) there is a decrease in sensitivity to moisture content.

5.3. Contribution to knowledge

As set out in Chapter 1, this PhD project forms a component part of an EPSRC funded project between Cranfield University and the University of Exeter (grant ref EP/C512243/1) and represents the foundation research for future work on the assessment of human-natural turf pitch interaction.

This research project represents a pioneer study of human biomechanical behaviour simultaneously with surface mechanical behaviour via a novel integrated approach. This was a two stage methodology: firstly, laboratory-based biomechanical testing to assess the stresses of human players performing typical sports movements on a variety of NTPs; and secondly, laboratory-based dynamic compression testing of surface materials to determine surface elastic-plastic behaviour in response to those stresses applied by players. Such an integrated approach is a development towards a more accurate, and complete, human-natural surface behaviour model.

The practical significance of this finding for future research is important as it increases awareness of how biomechanical parameters of human movement may also respond to changes in mechanical properties of a natural turf surface when they are modified to alter wear and degradation characteristics. Despite the fact that within the range of soil properties tested there was no modification of movement, it has been suggested that such alterations can affect not only sports performance but also potentially injury risk (Stover, 2003). The research project sets a precedent assessing the behaviour of a variety of NTPs, showing that the difference in soil type must be understood when dealing with NTPs. The research shows that it is not sufficient or appropriate to amalgamate all NTPs in studies of injury or biomechanics and separation by soil type and moisture content must be considered.

The project has a wide-ranging impact upon the disciplines of sports surface engineering, biomechanics and sports equipment research. This impact applies to end-users ranging from sports engineers, surface managers and players. In addition, the present study provides a background that will assist future studies to assess important aspects of human-natural turf interaction. The increased understanding of how humans interact with NTPs will help sports engineers in future surface and footwear design to improve performance and reduce the risk of player injury. A better understanding of the relationship between natural turf surface strength and moisture will provide a significant benefit to research in biomechanics and sports injury medicine and also to sport governing bodies and facilities providers who will benefit from improved surface quality that will attract viewers and assist international competitiveness from athletes. Players of both elite and recreational levels will benefit from improved surface performance, durability and safety, which will help promote participation in sport, which in turn should improve the health, wellness and well-being profile of the nation.

The project has generated a unique dataset and developed MATLAB code to analyse how humans respond to changes in natural turf properties underfoot. The code that allows user improvements and represents a powerful tool compared to the standard commercial software and provides loading and pressure rate data. The Mohr-Coulomb soil parameters and the surface stiffness data are an important input for the development of soil models that could be used for the development of footwear design and also to be inputted into models of the human body. Ideally, an ideal model of soil-turf system would include dynamic data (not quasi-static data) to account for the rate-dependent aspect of behaviour in response to player load. The project provides two specific data sets for two of the most common soils in sport from which empirical models to predict soil shear strength and stiffness as a function of bulk density and moisture could be developed. This database could be expanded by gradually reducing the soil percentage of sand starting from the current sand-based condition until the clay-based condition is reached. Such data can be applied in soil models of traction and stiffness. For example, the traction model developed by Godwin et al. (2007) predicts peak shear force at the point of shear failure as a function of soil parameters and implement geometry. This model could be fed with the Mohr-Coulomb soil mechanics data and adapted for a set of studs (interacting tines) to be used to determine the shear force on the boot sole, which will help footwear design. Project soil stiffness data could also be used to be inputted into models of human body to study the effect of how different natural turf surfaces affect the biomechanics of players.

5.3.1. Publications from this study

- Stiles VH, Dixon SJ and James IT (2006) *An initial investigation of human-natural turf interaction in the laboratory*. The Engineering of Sport 6, Vol 3: Developments for Innovation, 255-260. In: Proceedings of the 6th international conference on the engineering of sport, 10–14 July 2006, Olympic Hall, Munich, Germany.

- Stiles VH, Dixon SJ, Guisasola IN and James IT (2007) *Biomechanical response to variations in natural turf surfaces during running and turning.* Science, Technology and Research into Sport Surfaces (STARSS 2007). Loughborough, 2007.

- Stiles VH, Dixon SJ, Guisasola IN and James IT (2008) *Kinematic response to variations in natural turf during running*. In: Proceedings of 7th ISEA Conference, 2008 June 2-6 Biarritz.

- Stiles VH, Dixon SJ, Guisasola IN and James IT (2008) *Natural turf surfaces: the case for continued research*. Sports Medicine. Accepted, in press.

- James IT, Guisasola IN (2008) *Soil Management for Turf and Player Performance*. Presented to the Australian Turfgrass Conference, 2008 July, Melbourne, Victoria.

- Guisasola IN, James IT, Llewellyn C, Stiles VH and Dixon SJ (2008) *Human-surface interactions: an integrated study*. (In progress)

Full copies of these papers can be found in the Appendix E.

5.4. Evaluation of the research and further work

5.4.1. Research limitations from the biomechanical study

As exposed in Chapter 3 this research study incorporated different types of natural turf soil media into the biomechanics laboratory through the use of portable plastic trays in order to analyse biomechanical human response during sports performance with changes in natural turf mechanical properties. From a biomechanical perspective it is of primary importance to establish whether the natural turf conditions produced and incorporated into the laboratory are representative in terms of how humans perform typical movements on them compared to an outdoor sport pitch. In this sense, the incorporation of natural soil media into the biomechanics laboratory presents a difficult challenge when it comes to providing suitable rooting depths to produce required turf stability and frictional coefficients that will allow players to perform properly. The portable natural turf runway solution was a reasonable attempt to overcome the limitations of incorporating natural turf soil media into the biomechanics laboratory. The approach required natural turf to be transplanted into plastic trays (0.60 m x 0.40 m x 0.05 m), adequate to obtain the minimum rooting network to provide enough stability to simulate NTPs found outdoors. However, the limitations of this natural turf runway design include turf material shrinkage with variation of moisture content resulting in uneven runway aesthetics and increasing the risk of sporadic encounters with tray edges by the players, which could lead to variations in player step stride patterns affecting the biomechanics parameters. To overcome most of these problems, the use of a non disruptive surface facility similar to the soil bin used by Dixon et al. (2008) where turfgrass could be introduced would be preferred for further research on the subject.

The use of bigger containers to construct the natural turf runway such as the turf modules (1.2 m x 1.2 m x 0.2 m) supplied by GreenTech Systems (Bridgend, UK) would provide a more robust natural turf runway in the laboratory that could overcome the edge problem encountered in the present design, in that the new tray walls will fold down to join the neighbour producing a modular system without disturbing edges, improving the runway aesthetic and reduce stride pattern variations. However, due to the bigger size of the container some modification should be worked out in order to accommodate the force plate (0.6 m x 0.4 m). The extra depth will allow for a greater rooting system development and a more reliable determination of the soil mechanical properties 'in situ' however, these dimensions imply that each one of the modules will weight approximately 500 kg, 25 times more than the trays used for this study. The extra weight will increase the weight over the force plate tray from 20 kg to 80 kg, which may reduce the sensitivity of force measurement and increase the concerns about to what extent the measured force is representative of that on the player. Manual handling will not be possible and a special pallet fork/truck will have to be used, making the access to the force plate more difficult and reducing the mobility in the laboratory. Compaction by manual rolling will not be suitable and a mechanical press would need to be used to achieve an even compaction throughout the whole tray, increasing cost and making the process of incorporating and sustaining turf in a biomechanics laboratory environment potentially more complex and more time consuming.

In this study, human-surface interaction was assessed using laboratory-based natural turf surfaces. The reasons explained above demonstrate the difficulty of introducing natural turf in a laboratory environment. Moreover, sustaining natural turf growth in a laboratory environment is complicated due to the reduced capacity for natural turf to survive indoors away from fresh air and direct sunlight. When using a portable surface system it is very difficult to replicate a field conditions for anything but sand-based pitches as the real soil structural units (the soil aggregates) cannot be mimicked for such limited depths and settling times. It would be better to test outside the laboratory using field-based natural turf surfaces which represent a more sensible approach to the problem of assessing human-natural surface interaction. An outdoor approach would allow reconstructing natural game-play movements together a greater degree of freedom of movement. In this sense, it is recommended that the bigger containers described above are used for outdoor biomechanical testing as an existing sports field could be difficult to control in terms of soil properties.

The motion analysis hardware used in this experiment is based on infra-red technology which limits its capability outdoors due to reflections and lighting. An alternative method to collect 3D motion in outdoor conditions could use high sampling rate digital cameras (Carré and Kirk, 2007). To avoid manual digitising and making use of image analysis techniques, similar identification and tracking algorithms of anatomical markers to those used by conventional motion analysis systems could be designed in a commercial software package such as MATLAB to determine kinematic data in three dimensions.

The pressure insole devices are portable and can be used either in or outside of the laboratory. This study has shown the ability of such devices to detect subtle changes in pressures under the foot in response to variations in natural turf mechanical properties and player running behaviour. If synchronised force data in three dimensions needs to be determined, a device capable of measuring the other two horizontal orthogonal components, which the insole system cannot account for, would be necessary. There are commercial portable platforms for force and timing measurements such as the Accupower (AMTI, Watertown, Massachusetts) that have been proved to be valid and reliable (Walsh et al., 2006) that could probably be installed in an outdoor natural turf runway to give a more complete representation of player behaviour.

5.4.2. Research limitations from the mechanical study

Despite the fact that significant differences between surfaces were not determined using such portable mechanical devices, the theta probe and the Clegg Impact Hammer (CIH) used during the biomechanical testing provided useful information to control the state of the NTP at all times and are recommended in any further research on NTP. The different textures and densities selected suggested surfaces would have different mechanical behaviours (cushioning and frictional properties) for the variety of natural turf conditions tested, however it is uncertain whether those mechanical differences were too small to be detected using the CIH as it is was found out with player kinematics.

The devices were limited for assessing the mechanical properties of the range of NTPs within the experiment. The Clegg Impact Hammer (0.5 kg) could have been too light to penetrate the turf and soil and so could be influenced more by the grass than the soil and so that could explain why the greater differences expected from a soil texture point of view were not detected. It is suggested that the use of a heavier hammer (2.25 kg) could be more suitable to determine the soil-turf matrix hardness without causing too much damage to the surface. The lack of a smooth surface was seen to produce inconsistent data from the Clegg hammer in the study of turning movements and so it is not recommended its use in this case without modification of the device.

The shear vane device used to measure shear strength suffered from the depth limitation of the portable system selected to build the turf runways. The compaction of the surfaces over time reduced the soil volume available for the correct operation of the vane, which needs to be inserted in the soil completely. It is suggested that unless the depth of the portable system is increased, a soil penetrometer (instead of the shear vane) would provide more accurate shear strength results, although these are very sensitive to moisture content (Bachmann et al., 2006). It would also provide information on stud penetration depth where studded footwear is used. As mentioned in Chapter 3, at the time of the experiments were performed only the devices used were available for the project.

The modified dynamic approach developed for determining soil dynamic stiffness discussed in Chapter 4 was sensible in that it overcame the incapacity to perform complete dynamic tri-axial testing with the available equipment for this study. This was due to the water pressure controllers that could not respond quickly enough to soil dynamic compaction by pumping water to maintain a constant pressure. The inability to carry out dynamic tri-axial testing prevented from calculating dynamic shear strength parameters. However, the dynamic uni-axial compression approach used demonstrated the effect of moisture and loading rate on stiffness, although peak loading rate was limited by the maximum axial actuator velocity in the soil mechanics equipment. The maximum peak loading rates obtained were one order of magnitude below the actual human loading rate when running which is in the range of 70-80 kN s^{-1}. That rate dependency of soil strength reinforces the importance of determining the mechanical properties of sports surfaces at the actual strain rates that players perform in sports. For the purpose of testing with the actual player loading rates, a 20 Hz machine at least would be required. Such equipment is rare world-wide and expensive. There are a few extremely expensive devices capable of simulating this kind of stress/strain dynamic rates on the market, with operating frequencies of up to 50 Hz, such as the Dynamic Hollow Cylinder Testing System (GCTS Testing Systems, Tempe, USA). A dynamic tri-axial approach will enable determination of not only impact cushioning parameters such the dynamic stiffness but also frictional parameters as a function of shear strength.

It is recognized that the approach followed in the present study suffers from border effects that could affect soil lateral free deformation. In this sense, a larger diameter plastic container would be advisable where possible to allow for free lateral movement as soil is compacted. Due to time constraints, the effect of grass rooting on dynamic stiffness could not be tested. It is suggested that further research introduces grass into the system so that a full description of the actual soil-turf matrix that makes up an NTP can be determined.

As proposed in Chapter 3, it is suggested that future work should determine kinematic human response when performing similar sports movements but with natural turf surface conditions that range from very wet to very dry sand and clay conditions. By creating a greater range of hardness or stiffness, it is hypothesised that kinematic differences would be observed. Such extreme conditions may introduce practical surface construction issues due to swelling and shrinking of clay-based surfaces, together with ethical requirements to ensure the safety of players at all times. By examining the full range of surface conditions of NTPs, the kinetic (vertical and horizontal) and kinematic differences of human interaction can be determined. If no more significant differences are found, then there would be more evidence to support the hypothesis that humans tend to maintain similar kinetic responses and movement characteristics with changes in natural turf surface, which would in turn permit the modification of surface mechanical properties of NTPs without increasing the risk of injuries.

6. CONCLUSIONS

The aim of the present research project was to increase understanding about the human-natural turf pitch (NTP) interaction. To achieve this aim, four key objectives were stated in Chapter 1. The following conclusions are aligned with those objectives:

1. Two natural sports surfaces, a high sand content rootzone material used in the construction of natural winter sports surfaces as modern elite sand construction soccer pitches, and a clay loam used in the construction of elite cricket pitches and similar to many local authority winter sports surfaces, were successfully reproduced using a portable pitch system and tested in the biomechanical laboratory to study the effect that changes in natural turf has on the performance of human participants when performing typical running and turning sports movements.

2. The stresses applied by nine participants and the human body geometry revealed changes for running on the above mentioned natural sports surfaces.

    a. Two subgroups within the nine participants were identified using k-means cluster analysis.

    b. Significantly greater ($p < 0.05$, $n = 8$) kinetic values for peak vertical rate-of-loading (dF_z^{max}) and peak pressure rate-of-loading (dP^{max}) were measured for Subgroup A running on the sand-based (153.18 ± 7.17 BW s^{-1}, 0.78 ± 0.06 BW mm^{-2} s^{-1}) compared to the clay-based NTP (125.05 ± 6.49 BW s^{-1}, 0.61 ± 0.06 BW mm^{-2} s^{-1}). The change measured in the previous variables for Subgroup B was non-significant with the change in surface.

    c. Subgroup B yielded significantly lower ($p < 0.05$, $n = 8$) initial ankle joint angles (α^i) compared to Subgroup A which revealed they were running flat-footed compared to Subgroup A who were running heel-toe.

    d. Although kinetic and kinematic differences between player subgroups were determined, there was no kinematic evidence that different subgroups modified their running behaviour based on the surface they performed on. This suggests that either players prefer to maintain similar leg geometries and stiffness when running on a variety of NTPs or alternatively, that the mechanical properties of the surfaces selected for the research may not have been sufficiently different to cause changes in player response during running.

e. In the same study, no significant kinetic differences were determined for the specific turning movement studied.

3. The effect of moisture, density and grass rooting on the elastic moduli and the shear strength of the soil materials studied in the above mentioned natural sports surfaces were determined using quasi-static tri-axial compression.

    a. In general, the values of the mechanical parameters such as the bulk, Young's and shear modulus of both soil types increased significantly ($p < 0.05$) with increasing the bulk density.

    b. The clay-based soil presented a more acute change in mechanical properties with moisture content.

    c. Quasi-static stiffness of the sand soil followed a negative-quadratic model shape behaviour with moisture, presenting the maximum stiffness at an optimum moisture content, as a result of the cohesion that water adds to the material.

    d. The Mohr-Coulomb strength analysis revealed greater frictional components for the sand whereas greater cohesive components were determined for the clay-based material.

4. Dynamic soil behaviour was studied to determine material stiffness evaluated in response to the applied stress from the human participant over successive passes for running.

    a. The steady-state dynamic stiffnesses (k_d^{max}) measured at the highest rate-of-loading achievable with the equipment used for the experiment (6.5 kN s^{-1}) one order of magnitude lower than the one recorded in the biomechanical study, was significantly greater ($p < 0.001$) for the sand-based soil (84.4 ± 0.9 MN s^{-1}) than for the clay-based soil (33.5 ± 0.2 MN s^{-1}) as a result of a larger deformation of the clay-based material within the normal moisture content range for sports such as football.

    b. The stiffness was significantly increased with greater rates of loading for all the conditions, as the stress is applied more quickly to the soil, the time to deform reduces and the overall soil strength increases as a result.

    c. The dynamic results highlight the importance of the elastic-plastic behaviour of soils (or the soil-turf matrix) and the difference in dynamic mechanical behaviour between soil types. The plastic component of soils, or the soil-turf matrix, increases the contact time between the human and the surface (or the ball and the surface), reducing the peak impact loads on the body (or moderating ball rebound behaviour).

The elastic component is essential for energy return to the player (or ball) and for resilience or recovery of the grass-soil matrix material. A high sand content surface, unlike a high clay surface, will present a greater intrinsic stiffness that implies an increased elastic behaviour that should benefit sport performance (within limits). In turn, a reduced plastic deformation could imply greater peak load being transferred to the players and so it may imply a greater risk of injury.

Therefore, the present study furthers the understanding of how visco-plastic soil behaviour affects the player-surface interaction in sport and will inform engineering and management of how a biomechanical and mechanical integrated approach is the way forward to improve natural turf sports surfaces for greater sustainability, maximum usage at minimum risk of injury.

7. REFERENCES

Adams WA, Stewart VI, Thornton DJ (1971) *The assessment of sands suitable for use in sportsfields*. The J of the Sports Turf Research Institute, 47: 77-85.

Adams WA and Gibbs RJ (1994) *Natural Sport for Turf and Amenity: Science and Practice*. CAB International, Wallingford.

Anderson O and Reynolds W (2005) *Shin splints problems: How to strengthen the lower parts of your legs, and prevent (or repair) shin splints problems*. Retrieved from http://www.pponline.co.uk/encyc/0161b.htm, March, 2008.

Ashby MF (1972) *A first report on deformation-mechanism maps*. Acta. Metall., 20: 887-897.

Assimaki D, Kausel E and Whittle A (2000) *Model for dynamic shear modulus and damping for granular soils*. J of Geotechnical and Geoenvironmental Engineering, Vol 126, 10.

Bachmann J, Contreras K, Hartge KH et al. (2005) *Comparison of soil strength data obtained in situ with penetrometer and with vane shear test*. Soil & Tillage Research 87, 112-118.

Baker S (1991) *Temporal variation of selected mechanical properties of natural turf football pitches*. J of the Sports Turf Research Institute, 67: 83-92.

Baker S, Cook A and Adams W (1998) *Soil characteristics of first-class cricket pitches and their influence on playing performance.* J of Turfgrass Science, 74: 63-79.

Bates BT, Osternig LR, Sawhill JA et al. (1983) *An assessment of subject variability, subject-shoe interaction, and the evaluation of running shoes using ground reaction force data*. Journal of Biomechanics, 16 (3), 181-191.

Bates BT, Dufek JS and Davies HP (1992) *The effect of trial size on statistical power*. Medicine and Science in Sports and Exercise, 24 (9), 1059-1068.

Bates BT (1996) *Single-subject methodology: an alternative approach.* Medicine and Science in Sports and Exercise, 28 (5), 631-638.

Beard JB and Green RL (1994) *The Role of Turfgrasses in Environmental Protection and Their Benefits to Humans*. J Environ Qual, 23:452-460.

Blackburn S, Nicol A and Walker C (2005) *Development of a biomechanically validated turf testing rig*. In: Proceedings of the International Society of

Biomechanics 20th Congress – ASB 29th Annual Meeting; 2005 July 31- Aug 5; Cleveland, Ohio.

Bishop AW & Blight GE (1963) *Some aspects of effective stress in saturated and partly saturated soils*. Geotechnique, 13, 177-97.

Bobbert MF, Yeadon MR and Nigg BM (1992) *Mechanical analysis of the landing phase in heel-toe running*. Journal of Biomechanics, 25 (3), 223-234.

Bonstingl RW, Morehouse CA, and Nichol B (1975) *Torques developed by different types of shoes on various playing surfaces.* Med Sci Sports, 7: 127-131.

Brachet P, Blackburn S Nicol AC et al. (2003) *Body and limb accelerations during football activities on artificial turfs* [abstract]. In: Proceedings of the International Society of Biomechanics XIXth Congress; 2003 July 6-11: Dunedin, New Zealand, 39.

Brady NC and Weil RR (2002) *The Nature and Properties of Soils* (13th edition). New Jersey: Prentice Hall.

Brown RP (1987) *Performance tests for artificial sports surfaces.* Polymer Testing, 7: 279-292.

Bryman A and Cramer D (1997) *Quantitative data analysis with SPSS for windows*. Routledge: London.

BS 1377: 1990. London: British Standards Institution.

Bullock P, Newman AC and Thomasson AJ (1985) *Porosity Aspects of the Regeneration of Soil Structure after Compaction.* Soil and Tillage Research, 5, 325-341.

Butler RJ, Crowell HP and McClay DI (2003) *Lower extremity stiffness: implications for performance and injury*. Clinical Biomechanics, 18, 511-517.

Canaway PM (1975) *Fundamental techniques in the study of turfgrass wear: an advance report on research*. J of the Sports Turf Research Institute, 51, 104-115.

Canaway PM, Bell MJ (1986) Technical note: *an apparatus measuring traction and friction on natural and artificial playing surfaces*. J of the Sports Turf Research Institute, 62, 211-214.

Canaway PM and Baker SW (1993) *Concepts of playing quality: criteria and measurement.* Int. Turfgrass Soc. Res. J. 7:192-200.

Carman K (2002) *Compaction characteristics on towed wheels on clay loam in a soil bin*. Soil and Tillage Research, 65, 43-47.

Carré MJ, Kirk RF, Haake SJ (2007) *Developing Relevant Tests for Traction of Studded Footwear on Surfaces*. In: Fleming P, Young C, Dixon S, et al. 'STARSS 2007', Proceedings of the First International Conference of the SportSURF Network, 2007 September 17-18; Loughborough University, UK. ISBN 978-1-897911-30-3.

Cavanagh PR, LaFortune MA (1980) *Ground reaction forces in distance running*. Journal of Biomechanics, 13: 397-406.

Challis JH (2001) *The variability in running gait caused by force plate targeting.* Journal of Applied Biomechanics, 17, 77-83.

Chivers IH (1999) *Prescription Surface Development: Racetrack Management.* In Aldous DE, editor, International Turf Management Handbook. London: CRC Press, 299-310.

Claudio L (2008) *Synthetic Turf: Health debates takes root.* Environ Health Perspect, 116(3): A116–A122.

Clegg B (1976) *An impact testing device for in situ base course evaluation*. Proceedings of the Australian Road Research Bureau, 8, 1-6.

Cohen SZ, Nickerson S, Maxey R et al. (1990) *A groundwater monitoring study for pesticides and nitrates associated with golf courses on Cape Cod*. Groundwater Monit. Rev. (winter): 160-173.

Coyles VR and Lake MJ (1999) *Forefoot plantar pressure distribution inside the soccer boot during running*. In: Proceedings of the International Society of Biomechanics Footwear Biomechanics Group; 1999 Aug 5-7; Canmore, Canada.

Dabnichki P (1998) *Force measurement and calculation in sport activities*. In Haake SJ, editor, The Engineering of Sport. Cambridge: Blackwell Science, 317-324.

DCMS: *The Government's plan for sport: A sporting future for all*. Published by the Department for Culture Media and Sport (DCMS) 2001 [online]. Available from http://www.culture.gov.uk/Reference_library/Publications/archive_2001 [Accessed 2008 Mar 25].

De Wit B, De Clercq D and Aerts P (2000) *Biomechanical analysis of the stance phase during barefoot and shod running*. Journal of Biomechanics, 33, 269-278.

Dick RW, Schmalz R, Diehl N et al. (2003) *A review of game injuries by surface and injury mechanism in NCAA intercollegiate sports*. In Nigg BM, Cole GK, Stefanyshyn DJ, editors, Sports Surfaces; 2003. Canada: The University of Calgary. 2003; 107-123.

Dickinson JA, Cook SD, and Leinhardt TM (1985) *The measurement of shock waves following heel strike while running.* Journal of Biomechanics, 18, 415-422.

Dixon SJ, Batt ME, Collop AC et al. (1998) *The biomechanical and mechanical performance of Sureflex® sports surface material*. In Haake SJ, editor,The Engineering of Sport, 191-198. Blackwell: University Press, Cambridge.

Dixon SJ, Batt ME and Collop AC (1999) *Artificial playing surfaces research: a review of medical, engineering and biomechanical aspects*. Int J Sports Med, 20: 209-218.

Dixon SJ, Collop AC and Batt ME (2000) *Surface effects on ground reaction forces and lower extremity kinematics in running.* Medicine and Science in Sports and Exercise, 32 (11), 1919-1926.

Dixon SJ and Stiles VH (2003) *Impact absorption for tennis shoe-surface combinations*. Sports Engineering, 6 (1), 1-9.

Dixon SJ, James IT and Blackburn DWK et al. (2008) *Influence of footwear and soil density on loading within the shoe and soil surface during running*. Proc. I MechE Vol 222 Part P: J Sports Engineering and Technology.

Dura JV, Hoyos JV, Lozano L et al. (1999) *The effect of shock absorbing sports surfaces in jumping*. Sports Engineering, 2, 103-108.

Dychko B (1998) *The standardization of biomechanical analysis of ground reaction forces in sport*. In Haake SJ, editor, *The Engineering of Sport,* 261-264. Blackwell Science, Cambridge.

Eils E, Streyl M, Linnenbecker S, et al. (2004) *Characteristic plantar pressure distribution patterns during soccer-specific movements*. The Am J Sports Med, 32: 140-145.

Ekstrand J, Timpka T and Hägglund M (2006) *Risk of injury in elite football played on artificial turf versus natural grass: a prospective two-cohort study*. Br J Sports Med, 40: 975-980.

Ferris DP, Louie M and Farley CT (1998) *Running in the real world: adjusting leg stiffness for different surfaces*. Proceedings of the Royal Society: Biological Sciences, 265, 989-994.

Ferris DP, Liang K and Farley CT (1999) *Runners adjust leg stiffness for their first step on a new running surface*. Journal of Biomechanics, 32, 787-794.

Field TR (1994) *Horse Racing Tracks*, in Adams, W.A. and Gibbs, R.J. (1994) *Natural Turf for Sport and Amenity: Science and Practice*. Wallingford: CAB International, 329-353.

Fiolkowski P and Bauer J (1997) *The effects of different dance surfaces on plantar pressures.* J Dance Med Sci, 1:62-66.

Fleming PR, Young C, Roberts JR et al. (2005) *Human perceptions of artificial surfaces for field hockey*. Sports Engineering, 8: 121-136.

Ford KR, Manson NA, Evans BJ. et al. (2006) *Comparison of in-shoe loading patterns on natural grass and synthetic turf*. J Sci Med Sport, 9: 433-440.

Frederick EC, Clarke TE and Hamill CL (1984) *The effect of running shoe design on shock attenuation*. In Frederick EC, editor, Sports shoes and playing surfaces. Champaign, (IL): Human Kinetics, 190-198.

Fredlund DG and Rahardjo H (1993) *Soil mechanics for unsaturated soils*. New York: Wiley.

Fredlund MD, Wilson GW and Fredlund DG (1997) *Indirect Procedures to Determine Unsaturated Soil Property*. In: Proceedings of the 50th Canadian Geotechnical Conference Golden Jubilee Conference Ottawa, Ontario, Canada, K1S 5B6, October 20 - 22, 1997.

Fry J and Huang B (2004) *Applied Turfgrass Science and Physiology*. New Jersey: John Wiley and Sons.

Fuller CW, Dick RW, Corlette J, et al. (2007) *Comparison of the incidence, nature and cause of injuries sustained on grass and new generation artificial turf by male and female football players*. Part 2: training injuries. Br J Sports Med, 2007 41 SI: i27-i32.

Fry J and Huang B (2004) *Applied Turfgrass Science and Physiology*. New Jersey: John Wiley and Sons.

Garcia AC, Martinez A, Solaz JS, et al. (1999) *Development of a method for measuring horizontal forces in soccer boots studs during skills performance.* In: Proceedings of the International Society of Biomechanics Footwear Biomechanics Group; 1999 Aug 5-7; Canmore, Canada.

Gaskin G.J and Miller JD (1996) *Measurement of Soil Water Content Using a Simplified Impedance Measuring Technique*. J. agric. Eng Res. 63, 153-160.

Gasser JKR (1973) *An assessment of the importance of some factors causing losses of lime from agricultural soils*. Experimental Husbandry 25, 86-95.

Gold AJ, DeRagon WR, Sullivan WM et al. (1990) *Nitrate-nitrogen losses to groundwater from rural and suburban land uses*. J Soil Water Conserv, 45: 305-310

Godwin RJ and Spoor G (1977) *Soil factors influencing work days*. Agriculture Engineer 32 (4): 87-90.

Godwin RJ, O'Dogherty MJ, Saunders C et al. (2007) *A force prediction model for mouldboard ploughs incorporating the effects of soil characteristic properties, plough geometric factors and ploughing speed*. Biosystems Engineering, 97, 117-129.

Green RL, Beard JB and Oprisko MJ (1991) *Root hairs and root lengths in nine warm-season turfgrass genotypes*. J. Am. Soc. Hortic. Sci. 116:965-969.

Gross CM, Angle JS and Welterlen MS (1990) *Nutrient and sediment losses from turfgrass*. J Environ Qual, 19: 663-668.

Hamill J, Bates BT and Holt KG (1992) *Timing of lower extremity joint actions during treadmill running*. Med Sci Sports Exerc, 24: 807-813.

Hamza MA and WK Anderson (2005) *Soil compaction in cropping systems. A review of the nature, causes and possible solutions*. Soil and Tillage Research. Vol 8 (2), 121-145.

Head KH (1982) *Manual of soil laboratory testing.* Plymouth: Pentech Press.

Hennig EM (2002) *Plantar pressures, shock and rearfoot motion during running - Are these meaningful quantities for the prediction of running injuries?* In: 4th World Congress of Biomechanics. Calgary: Omnipress-CD, pp. CD-5285.pdf, 2002.

Herrick JE and Jones TL (2002) *A dynamic cone penetromter for measuring soil penetration resistance*. Soil Science Society of America Journal 66: 1320-1324.

Hodgson L, Standen PJ, Batt ME (1998) *Effects of seasonal change in rugby league on the incidence of injury*. Br J Sports Med, 32: 144-148.

Holmes G and Bell MJ (1986) *A pilot study of the playing quality of football pitches*. Journal of the Sports Turf Research Institute, 62, 74-90.

Hooker P (2002) *The development of Automated Testing in Geotechnical Engineering*. In: Proceedings of the Indian Geotechnical Conference, Vol. 1, December 2002, 96-102.

Horn R (2004) *Time Dependence of Soil Mechanical Properties and Pore Functions for Arable Soils*, Vol 68 (4), J of Soil science society of America.

IOG (2001) *Guidelines for performance quality standards part one; sports surfaces natural and non turf*. Milton Keynes, UK: The Institute of Groundsmanship.

IOG (2008) *The State of the Groundsmanship Industry*. Presented at the IOG Annual Conference, February 2008, Liverpool, UK.

James IT, Dixon SJ, Blackburn K et al. (2006) *The measurement of applied pressure at depth with two natural soil surfaces at different densities*. The Engineering of Sport 5, Vol 2: 173-178.

James SL, Bates BT and Osternig LR (1978) *Injuries to runners*. The Am J Sports Med, 6: 40-50.

Jennings-Temple M, Leeds-Harrison P, James IT (2006) *An investigation into the link between soil physical conditions and the playing quality of winter sports pitch rootzones*. In: Abstracts from the 6th international conference on the engineering of sport, 10–14 July 2006, Olympic Hall, Munich, Germany.

Karmakar S, Kushwaha R (2005) *CFD Simulation of Soil Forces on a Flat Tillage Tool*. The society for Engineering in agricultural, food and biological systems. In: Proceedings for ASAE Annual International Meeting, Tampa, Florida, 17 - 20 July 2005.

Kerdok AE, Biewener AA, McMahon TA et al. (2002) *Energetics and mechanics of human running on surfaces of different stiffnesses*. *J Appl Physiol,* 92: 469-478.

Kolitzus HJ (1984) *Functional standards for playing surfaces*. In Frederick EC, editor, Sport shoes and playing surfaces: Biomechanical properties. Champaign (IL): Human Kinetics Pubishers Inc, 98-118.

Kolitzus HJ (2003) *Covering the overlooked in standards - measuring the technical characteristics of synthetic fields over time and the implications for long-term maintenance issues*. Published online. http://www.isss.ed/conferences/amsterdam2003/kolitzus.pdf [Accessed on March 2008].

Kulhawy FH and PW Mayne (1990) *Manual on Estimating Soil Properties for Foundation Design*. Report EPRI-EL6800. Palo Alto, CA: Electric Power Research Institute.

Lafortune MA, Morag E and Pisciotta J (2003) *Sports surface and athletic footwear creation*. In Nigg, BM, Cole GK, Stefanyshyn DJ editors. Sports Surfaces. The University of Calgary, Canada, 217-232.

Lambson RB, Barnhill BS and Higgins RW (1996) *Football cleat design and its effect on anterior cruciate ligament injuries. A three-year prospective study*. Am J Sports Med, 24: 155-159.

Lees A and Nolan L (1998) *The Biomechanics of soccer: A review*. Journal of Sports Sciences, 16, 211-234.

Lejeune TM, Willems PA and Heglund NC (1998) *Mechanics and energetics of human locomotion on sand.* J Exp Biology, 201: 2071-2080.

Levy IM, Skovron ML, Agel J (1990) *Living with artificial grass: A knowledge update.* The American Journal of Sports Medicine 18: 406-412.

Light LH, MacLellan GE, and Klenerman L (1979) *Skeletal transients on heel strike in normal walking with different footwear.* J Biomech, 13: 477-480.

Livesay GA, Reda DR and Nauman EA (2006) *Peak torque and rotational stiffness developed at the shoe-surface interface: the effect of shoe type and playing surface.* Am J Sports Med, 34: 415-422.

Martin PE, Heise GD and Morgan DW (1993) *Interrelationships between mechanical power, energy transfers, and walking and running economy.* Medicine & Science in Sports & Exercise. 25(4):508-515.

Martinez A, Dura JV, Duenas L, et al. (2004) *Artificial and natural turf: biomechanical differences between surfaces*. In: Proceedings for Fifth World Congress on Science and Football, J Sports Sci, 2004; 22: 494-495.

McGawon A, Qayyum TI, Beard JB et al. (1997) *Performance evaluation of turfgrass root zone materials and profile constructions using an innovative rapid, eccentric loading test method*. In: Proceedings of the International Turfgrass Research Conference. Sydney, July 1997.

McMahon TA and Greene PR (1984) In Frederick EC, editor, *Sport shoes and playing surfaces: Biomechanical properties,* 138-162. Human Kinetics: Champaign, IL.

Menzies BK, Hooker P, Sutton JA et al. (2002) *GDS software-based dynamic and seismic laboratory soil testing systems*. A GDS publication [online]. Available from http://www.gdsinstruments.com/support/gds_papers.htm. [Accessed 2008 Mar 20].

Meyers MC and Barnhill BS (2004) *Incidence, causes and severity of high school football injuries on fieldturf versus natural grass*. The Am J Sports Med, 32: 1626-1638.

Milburn PD and Barry EB (1998) *Shoe-surface interaction and the reduction of injury in rugby union*. J Sports Med, 25: 319-327.

Miller DI (1990) *Ground reaction forces in distance running*. In Cavanagh PR, editor, Biomechanics of distance running. Champaign, (IL): Human Kinetics, 203-223.

Millet G, Perrey S and Foiussac M (2006) *The role of engineering in fatigue reduction.* In: of the 5th International Conference on The Engineering of Sport, The engineering of Sports, Vol 3, Munich, 2006.

Morag E and Johnson DA (2001) *Traction requirements of young soccer players* [abstract]. In Hennig E, Stacoff A, editors, Proceedings of the Symposium on Footwear Biomechanics; 2001 July 5-7; Zurich: 2001: 62-63.

Nigg BM, Frederick EC, Hawes MR, et al. (1986a) *Factors influencing short-term pain and injuries in tennis*. Int J of Sport Biomech, 2: 156-165.

Nigg BM, Bahlsen AH, Denoth J et al. (1986b) *Factors influencing kinetic and kinematic variables in running*. In B.M. Nigg, editor, Biomechanics of Running Shoes, 139-159. Human Kinetics: Champaign, IL.

Nigg BM and Yeadon MR (1987) *Biomechanical aspects of playing surfaces*. J Sports Sci, 5: 117-145.

Nigg BM, Yeadon MR and Herzog W (1988a) *The influence of construction strategies of spring surfaces on deformation during vertical jumps*. Med Sci Sports Exerc, 20: 396-402.

Nigg BM and Segesser B (1988b) *The influence of playing surfaces on the load on the locomotor system and on football and tennis injuries*. Sports Medicine, 5, 375-385.

Nigg BM, Stefanyshyn DJ and Cole GK (2003) *Criteria for functional biomechanical testing of sport surfaces*. In B.M. Nigg GK, Cole GK and Stefanyshyn DJ, editors, *Sports Surfaces*, 311-334, University of Calgary.

Oliver THL and Casimaty BG (1998) *High performance natural turf sportfields to meet the demand of 21st century stadia*. In Proceedings for the International Conference 'Stadia 2000' Thompson PD, Tolloczko JJA, Clarke JN, Concrete Society, Taylor and Francis, 1998.

Orchard J (2001) *The AFL Penetrometer study: Work in progress*. J Sci Med Sport, 4: 220-232.

Orchard J (2002) *Is there a relationship between ground and climatic conditions and injuries in football*? J Sports Med, 32: 419-432.

Orchard J, Chivers IH, Aldous DE, et al. (2005) *Rye grass is associated with fewer non-contact anterior cruciate ligament injuries than Bermuda grass*. Br J Sports Med, 39: 704-709.

Pratt GW (1984) *Racing surfaces - A survey of mechanical behaviour*, In: Proceedings of the 30th Annual Convention of the American Association of Equine Practitioners. 321-331.

Richards CW and Baker SW (1992) Technical note: *The effect of sward height on ball roll properties for association football*. *Journal of the Sports Turf Research Institute,* 68, 124-127.

Rodano R (1983) *Analysis of the impact in running shoes*. In B.M. Nigg & B.A. Kerr, editors. In: Proceedings of the International Symposium on Biomechanical aspects of sport shoes and playing surfaces, 35-42. University of Calgary.

Rodriguez Diaz JA, Knox JW and Weatherhead EK (2007) *Competing demands for irrigation water: gold and agriculture in Spain.* Irrig. And Drain. (in press) Published online in Wiley InterScience (www.interscience .wiley.com).

Rogers III JN and Waddington DV (1990) *Portable apparatus for assessing characteristics of athletic field surfaces*. *In*: Schmidt, R.C., Hoerner EF, Milner EN and Morehouse CA, editors. Natural and artificial playing fields: characteristics and safety features, Phoenix, Arizona, Philadelphia: ASTM, 96-110.

Schneider JA, Hoyos L Jr, Mayne PW et al. (1999) *Field and laboratory measurements of dynamic shear modulus of Piedmont residual soils*. Behavioral Characteristics of Residual Soils, GSP 92, ASCE, Reston, VA, 12-25.

Scott HD (2000) *Soil Physics: Agricultural and Environmental Applications*. Ames: Iowa State University Press.

Scott RA and Pearce RW (1976) *Soil compaction by impact*. *Ground Treatment by Deep Compaction*. Symposium Report. Institution of Civil Engineers.

Shipton, P.M.R. (2008). *The optimisation of cricket pitch rolling*. Cranfield University, PhD Thesis (unpublished).

Shorten MR (2000) *Running shoe design: protection and performance*. In D. Tunstall Pedoe editor, Marathon Medicine, 159-169. Royal Society of Medicine: London.

Shorten MR and Himmelsbach JA (2002) *Shock attenuations of sports surfaces*. In S. Ujihashi and S.J. Haake editors, The engineering of sport IV: Proceedings of the 4th International Conference on The Engineering of Sport, Kyoto, Japan. Blackwell Science: Oxford.

Shorten M, Hudson B and Himmelsbach J (2003) *Shoe-surface traction of conventional and in-filled synthetic turf football surfaces*. In: Proceedings of International Society of Biomechanics XIXth Congress; 2003 July 6-11; Dunedin, New Zealand; 360.

Smith N, Dyson R and Hale T (2002) *The effects of sole configuration on ground reaction force measured on natural turf during soccer specific actions*. In: Spinks W, Reilly T, Murphy A, editors. Science and Football IV. London: Routledge, 2002: 44-49.

Smith N, Dyson R and Janaway L (2004) *Ground reaction force measures when running and jogging in soccer boots and soccer training shoes on a natural turf surface.* Sports Eng, 7: 159-167.

Smith J, Smith P and Addiscott T (1996) *Quantitative Methods to Evaluate and Compare Soil Organic Matter (SOM) Models.* In Powlson DS, Smith P and Smith PU editors. *Evaluation of Soil Organic Matter Models*, Nato ASI Series, 138, 181-199.

Spoor G, Tijink FGJ and Weisskopf P (2003) *Subsoil compaction: risk, avoidance, identification, and alleviation.* Soil & Tillage Research 73, 175-182.

Stefanyshyn DJ, Baroud G and Nigg BM (2001) *The potential of structured surfaces.* Book of Abstracts of the 6th Annual Congress of the European College of Sport Science, 90.

Stefanyshyn DJ, Stergiou P, Lun VMY et al. (2006) *Knee angular impulse as a predictor of patellofermoral pain in runners*. The American J of Sports Medicine 34: 1844-1851.

Steffen K, Andersen TE and Bahr R (2007) *Risk of injury on artificial turf and natural grass in young female football players*. Br J Sports Med, 2007; 41 SI: i33-i37.

Stergiou N and Bates BT (1997) *The relationship between subtaler and knee joint function as a possible mechanism for running injuries*. Gait and Posture, 6: 177-185.

Stiles VH and Dixon SJ (2006) *The influence of different playing surfaces on the biomechanics of a tennis running forehand foot plant*. J Appl Biomech, 22:14-24.

Stiles VH, Dixon SJ and James IT (2006) *An initial investigation of human-natural turf interaction in the laboratory*. The Engineering of Sport 6, Vol 3: Developments for Innovation, 255-260. In: Proceedings of the 6th international conference on the engineering of sport, 10–14 July 2006, Olympic Hall, Munich, Germany.

Stiles VH, Dixon SJ, Guisasola IN and James IT (2008) *Natural turf surfaces: the case for continued research*. Sports Medicine. In press.

Stiles VH. Personal email communication, 16th June 2008.

Stover SM (2003) *The Epidemiology of Thoroughbred Racehorse Injuries', ClinicalTechniques in Equine Practice*, 2 (4), 312-322.

Terzaghi K (1943) *Theoretical Soil Mechanics*, John Wiley, New York.

Terzaghi K and Peck RB (1948) *Soil Mechanics in Engineering Practice*, John Wiley, New York.

Tillman MD, Fiolkowski P, Bauer JA et al. (2002) *In-shoe plantar measurements during running on different surfaces: changes in temporal and kinetic parameters*. Sports Eng, 5: 121-128.

Torg J, Quendenfeld T and Landau B (1974) *The shoe-surface interface and its relationship to football knee injuries*. J Sports Med, 2: 261-269.

Valiant GA (1990) *Transmission and attenuation of heel strike accelerations.* In Cavanagh PR, editor. Biomechanics of distance running. Champaign, (IL): Human Kinetics, 225-247.

Vaughan CL, Davis BL and O'Connor JC (1992) *Dynamics of Human Gait*. Human Kinetics: Champaign, IL.

Vucetic M and Dobry R (1991) *Effect of soils plasticity on cyclic response.* Journal of Goetechnical Engineering, ASCE, 117 (1), pp. 898-907.

Walsh MS, Ford KR, Bangen KJ et al. (2006) *The validation of a portable force plate for measuring force-time data during jumping and landing tasks*. J of Strength and Conditioning Research, 20, 4, 730-734.

Whitlow R (2001) *Basic Soil Mechanics* (4th edition). London: Prentice Hall.

Vincent WJ (1995) *Statistics in Kinesiology*. Human Kinetics: Champaign, IL.

Wulfsohn D, Adams BA and Fredlund DG (1999) *Triaxial Testing of Unsaturated Agricultural Soils*, J. agric. Engng Res, 69, 317-330.

Yin J and Graham J (1999) *Elastic viscoplastic modelling of the time-dependent stress-strain behaviour of soils* [abstract]. Can Geotech J, 34 (4): 736-745.

Young C, Fleming PR (2007) *A review of mechanical impact testing devices for ort surfaces*. In: Fleming P, Young C, Dixon S, et al. 'STARSS 2007', Proceedings of the First International Conference of the SportSURF Network, 2007 September 17-18; Loughborough University, UK. ISBN 978-1-897911-30-3.

Zebarth BJ and Sheard RW (1985) *Impact and Shear Resistance of Turf Grass Racing Surfaces for Thoroughbreds*, American Journal of Veterinary Research, 46 (4), 778-784.

Zheng-Yi F and Sutter KG (2000) *Dynamic Properties of Granulated Rubber/Sand Mixtures*. GeotechnicalTesting Journal, GTJODJ, Vol. 23 (3), 338–344.

8. APPENDIX A: Soil nutrient analyses

Contact : DR IAIN JAMES
LECTURER IN APPLIED
SOIL SCIENCE NSRI
CRANFIELD UNIVERSITY
SILSOE
BEDFORD MK45 4DT
Tel. : 01525 863037

G147

Please quote the above code for all enquiries

Client :

Sample Matrix : Agricultural Soil

Laboratory Reference
Card Number 06626/06

Date Received 24-Apr-06
Date Reported 28-Apr-06

Samples will be stored until 24-MAY-2006

SOIL ANALYSIS REPORT

Laboratory Sample Reference	Field Details		Soil pH	Index			mg/l (Available)		
	No.	Name or O.S. Reference with Cropping Details		P	K	Mg	P	K	Mg
27922/06	1	C *No cropping details given*	**7.8**	**4**	**3**	**3**	**49.2**	**367**	**142**
27923/06	2	R *No cropping details given*	**7.2**	**1**	**0**	**0**	**12.2**	**17**	**13**
27924/06	3	S *No cropping details given*	**7.8**	**3**	**2+**	**3**	**32.8**	**234**	**109**

If general fertiliser and lime recommendations have been requested, these are given on the following sheets.
The analytical methods used are as described in DEFRA Reference Book 427
The index values are determined from the DEFRA Fertiliser Recommendations RB209 7th Edition (Appendix 4).

Released by *V Castle* On behalf of NRM Ltd Date *28/04/06*

MICRO NUTRIENT REPORT

DATE **28th April 2006**

SAMPLES FROM

DR IAIN JAMES
LECTURER IN APPLIED
SOIL SCIENCE NSRI
CRANFIELD UNIVERSITY
SILSOE
BEDFORD MK45 4DT
Tel: 01525 863037
Fax: 01525 863366

Report reference : **06626/27922/06-1** Field Name : **C** Field Size :

Crop : Soil Type : **Medium** Soil pH : **7.8**

COPPER	Result	Very Low	Low	Risk	Normal	Becoming Excessive
EDTA Extractable Copper mg/l	**6.8**					

BORON	Result	Very Low	Low	Risk	Normal	Becoming Excessive
Hot Water Soluble Boron mg/l	**1.7**					

ZINC	Result	Very Low	Low	Risk	Normal	Becoming Excessive
EDTA Extractable Zinc mg/l	**8.4**					

Comments : High available zinc levels in soil can occur naturally or may be as a result of sludge, slurry or manure applications year on year. The soil should be tested for the total zinc level (and any other potentially toxic heavy metals) to check that levels have not become excessive due to organic manure applications.

IRON	Result	Very Low	Low	Risk	Normal	Becoming Excessive
DPTA Extractable Iron mg/l	**82.7**					

ORGANIC MATTER	Result	Very Low	Low	Risk	Normal	High
Organic Matter (Wet Oxidation) %	**2.8**					

Report continued……

Cranfield UNIVERSITY

MICRO NUTRIENT REPORT

DATE **28th April 2006**

SAMPLES FROM

DR IAIN JAMES
LECTURER IN APPLIED
SOIL SCIENCE NSRI
CRANFIELD UNIVERSITY
SILSOE
BEDFORD MK45 4DT
Tel: 01525 863037
Fax: 01525 863366

Report reference : **06626/27922/06-2** Field Name : **C** Field Size :
Crop : Soil Type : **Medium** Soil pH : **7.8**

SULPHATE	Result	Very Low	Low	Risk	Normal	Becoming Excessive
Available (Phosphate Buffer Soluble) Sulphate mg/l	**309.9**					

Comments : Plants absorb sulphur as the sulphate ion. Sulphates are not retained in the soil, to any great extent, they are soluble and tend to move with the soil water and are readily leached by high rainfall or irrigation. This is particularly true for low capacity (sandy) soils. Sulphur behaves very much like nitrogen, the largest pool of sulphur is contained within the organic matter. The sulphate sulphur becomes available to the plant via bacterial breakdown of the organic matter, atmospheric sulphur and other forms of reduced sulphur. Intensification of agriculture, improved crop varieties, the use of sulphur free fertilisers and control of atmospheric pollution have aggravated the sulphur deficiency problem. In many UK soils, the distribution of sulphate sulphur may not be consistent throughout the soil profile. A profile test down to 90cm should be considered before using the soil test levels alone to calculate fertiliser sulphur requirements. If the soil has relatively high sulphur levels at lower depths, the amounts can be reduced. The best method of building soil sulphur reserves is by adding organic materials and maintaining an adequate organic matter content. Where satisfactory organic sulphur reserves cannot be maintained, certain fertilisers or amendments have to be used to supply the crop with its sulphur requirement.

MANGANESE	Result	Very Low	Low	Risk	Normal	Becoming Excessive
DPTA Extractable Manganese mg/l	**6.0**					

Comments : Some soils are naturally low in manganese. However, the availability of manganese may be reduced due to high soil pH (7.0 or above), very high or very low organic matter content, wet and/or poorly drained soil or a combination of these factors. Manganese is the most common trace element deficiency in UK field crops. Manganese deficiency is common but generally not severe on this type of soil and is usually associated with a high soil pH. Over liming is often the cause of induced manganese deficiency and symptoms may disappear after a rainfall. Beans, Oats, Onions, Wheat, Peas, Potatoes and Oilseed Rape respond well to applications of manganese when deficient.

Cranfield UNIVERSITY

MICRO NUTRIENT REPORT

DATE **28th April 2006**

SAMPLES FROM

DR IAIN JAMES
LECTURER IN APPLIED
SOIL SCIENCE NSRI
CRANFIELD UNIVERSITY
SILSOE
BEDFORD MK45 4DT
Tel: 01525 863037
Fax: 01525 863366

Report reference : **06626/27923/06-2** Field Name : **R** Field Size :

Crop : Soil Type : **Medium** Soil pH : **7.2**

COPPER	Result	Very Low	Low	Risk	Normal	Becoming Excessive
EDTA Extractable Copper mg/l	**1.0**					

Comments : Deficient soil copper status. Treatment recommended either as foliar spray or soil application for cereals and break crops.

BORON	Result	Very Low	Low	Risk	Normal	Becoming Excessive
Hot Water Soluble Boron mg/l	**0.3**					

Comments : Low soil boron status. Treatment recommended either as foliar spray or soil application for cereals and break crops.

ZINC	Result	Very Low	Low	Risk	Normal	Becoming Excessive
EDTA Extractable Zinc mg/l	**1.9**					

Comments : Zinc deficiency in UK soils is fairly uncommon. Symptoms may be seen if the spring growing conditions are cool and wet. However, crops sensitive to zinc will require either a foliar spray or soil application when the soil level is low. Beans, Maize, Fruit Trees (Apples) and Onions have a high response to zinc. Root Crops (including Potatoes and Sugar Beet), Barley, Strawberries and Tomatoes may be responsive to zinc under certain conditions.

IRON	Result	Very Low	Low	Risk	Normal	Becoming Excessive
DPTA Extractable Iron mg/l	**45.9**					

Report continued……

MICRO NUTRIENT REPORT

DATE 28th April 2006

SAMPLES FROM

DR IAIN JAMES
LECTURER IN APPLIED
SOIL SCIENCE NSRI
CRANFIELD UNIVERSITY
SILSOE
BEDFORD MK45 4DT
Tel: 01525 863037
Fax: 01525 863366

Report reference : **06626/27923/06-3** Field Name : **R** Field Size :

Crop : Soil Type : **Medium** Soil pH : **7.2**

ORGANIC MATTER	Result	Very Low	Low	Risk	Normal	High
Organic Matter (Wet Oxidation) %	**1.0**					

SULPHATE	Result	Very Low	Low	Risk	Normal	Becoming Excessive
Available (Phosphate Buffer Soluble) Sulphate mg/l	577.7					

MANGANESE	Result	Very Low	Low	Risk	Normal	Becoming Excessive
DPTA Extractable Manganese mg/l	**1.7**					

MICRO NUTRIENT REPORT

DATE **28th April 2006**

SAMPLES FROM

DR IAIN JAMES
LECTURER IN APPLIED
SOIL SCIENCE NSRI
CRANFIELD UNIVERSITY
SILSOE
BEDFORD MK45 4DT
Tel: 01525 863037
Fax: 01525 863366

Report reference : **06626/27924/06-3** Field Name : **S** Field Size :

Crop : Soil Type : **Medium** Soil pH : **7.8**

COPPER	Result	Very Low	Low	Risk	Normal	Becoming Excessive
EDTA Extractable Copper mg/l	**4.9**					

BORON	Result	Very Low	Low	Risk	Normal	Becoming Excessive
Hot Water Soluble Boron mg/l	**1.2**					

ZINC	Result	Very Low	Low	Risk	Normal	Becoming Excessive
EDTA Extractable Zinc mg/l	**2.9**					

Comments : Zinc deficiency in UK soils is fairly uncommon. Symptoms may be seen if the spring growing conditions are cool and wet. However, crops sensitive to zinc will require either a foliar spray or soil application when the soil level is low. Beans, Maize, Fruit Trees (Apples) and Onions have a high response to zinc. Root Crops (including Potatoes and Sugar Beet), Barley, Strawberries and Tomatoes may be responsive to zinc under certain conditions.

IRON	Result	Very Low	Low	Risk	Normal	Becoming Excessive
DPTA Extractable Iron mg/l	**61.6**					

ORGANIC MATTER	Result	Very Low	Low	Risk	Normal	High
Organic Matter (Wet Oxidation) %	**2.0**					

Report continued……

Cranfield UNIVERSITY

MICRO NUTRIENT REPORT

DATE **28th April 2006**

SAMPLES FROM

DR IAIN JAMES
LECTURER IN APPLIED
SOIL SCIENCE NSRI
CRANFIELD UNIVERSITY
SILSOE
BEDFORD MK45 4DT
Tel: 01525 863037
Fax: 01525 863366

Report reference : **06626/27924/06-4** Field Name : S Field Size :

Crop : Soil Type : **Medium** Soil pH : **7.8**

SULPHATE	Result	Very Low	Low	Risk	Normal	Becoming Excessive
Available (Phosphate Buffer Soluble) Sulphate mg/l	**85.6**					

MANGANESE	Result	Very Low	Low	Risk	Normal	Becoming Excessive
DPTA Extractable Manganese mg/l	**9.8**					

Cranfield UNIVERSITY

DATE 28th April 2006
SAMPLES FROM

SAMPLED BY

Report reference 06626/06-1

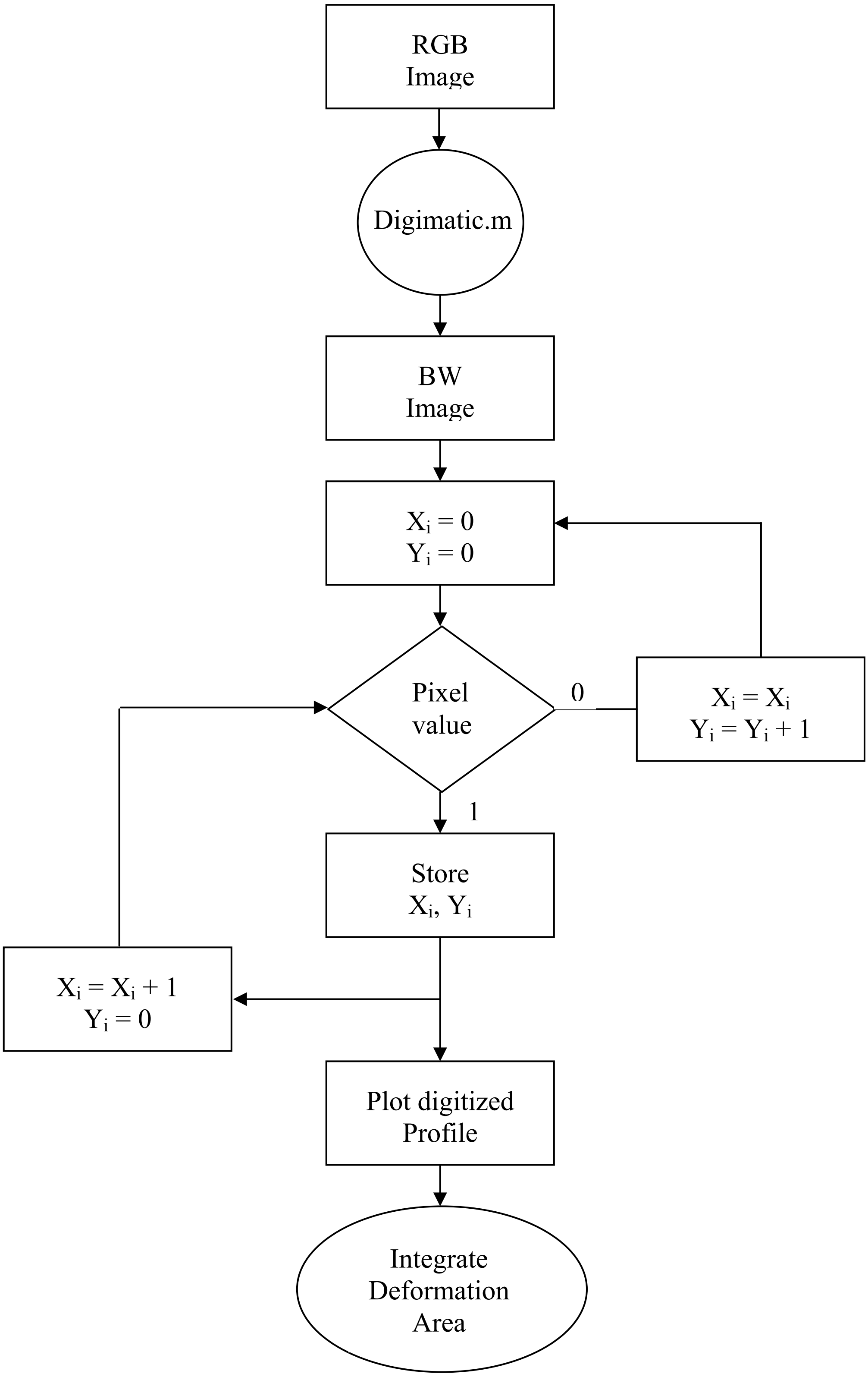
DR IAIN JAMES
LECTURER IN APPLIED
SOIL SCIENCE NSRI
CRANFIELD UNIVERSITY
SILSOE
BEDFORD MK45 4DT
Tel: 01525 863037
Fax: 01525 863366

Field Name Field Size Lab No. Soil Type	Last Crop	Next Crop	Recommendations Units/acre P_2O_5	K_2O	MgO	Additional Notes
C 027922						Good P status.
R 027923						Potassium deficiency may limit crop performance. Phosphate status low - additional nutrient required. Apply fertiliser to seedbed to help establishment. Apply a magnesium fertiliser to correct Mg deficiency. Copper deficiency. Soil is deficient of boron. Use boron only on sensitive crops.
S 027924						

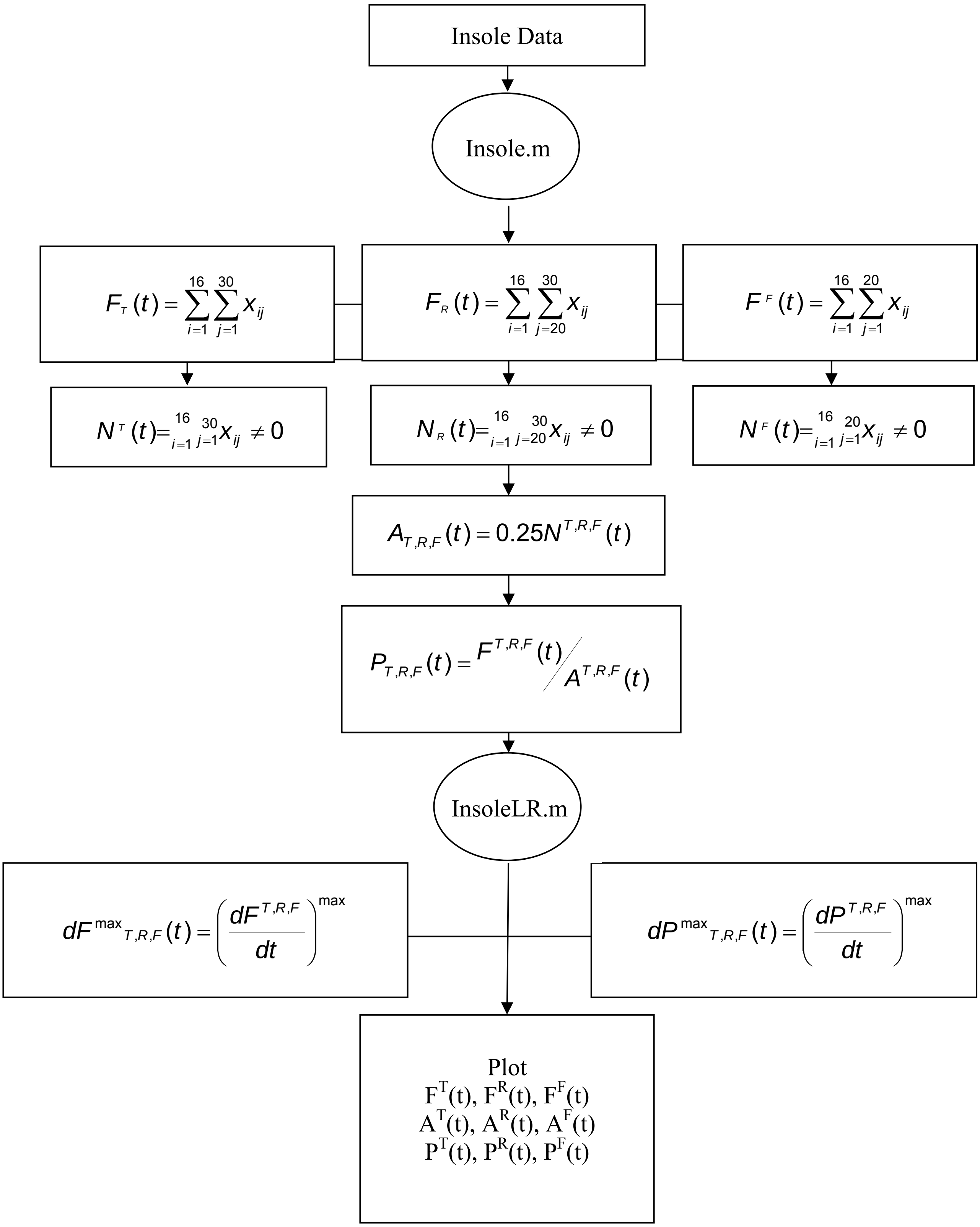
Fertiliser recommendations are based on **DEFRA RB209 (Seventh Edition - 2000)**. If a nutrient is deficient and no recommendation is given, either no recommendation is given in RB209 or we have insufficient data to give a recommendation.

9. APPENDIX B: Flow diagrams for MATLAB scripts

Flow diagram for the image analysis subroutine (Digimatic.m) developed in MATLAB to digitize footprint profiles. X and Y represent the location coordinates within the image.



Flow diagram for insole pressure data analysis. It includes the following subroutines: Insole.m and insoleLR. F, A and P represent the force, contact area, pressure and number of activated force transducer as a function of time (t) for a right single footstep, respectively. There are 4 transducers per cm^2. The subscripts T, R and F refer to the total, rear and fore right foot.



10. APPENDIX C: Clegg Impact Hammer Calibration Certificate

SDi SIMON DEAKIN INSTRUMENTATION

P.O. Box 2481, TROWBRIDGE, WILTSHIRE, BA14 9YJ ENGLAND
Telephone +44 (0)1225 355169 Fax +44 (0)1225 355893
e-mail: simon@sdinstrumentation.freeserve.co.uk
web site: www.sdinst.com VAT Reg. No. 713 3905 52

CLEGG IMPACT SOIL TESTER

Test and Calibration Certificate

Serial No 9097 Type CST/882 Date 3/5/05

The above Clegg Impact Soil Tester was tested and calibrated using an electronic Calibration Unit set to generate an output charge pulse equivalent to 200 gravities.

The Clegg Impact Soil Tester was calibrated to give a reading of 200 gravities.

The performance of the Tester was checked by dropping the 0.5 Kg hammer weight through the guide tube. The 0.5 Kg weight was positioned such that the raised section of the weight was flush with the top of the guide tube. The weight was allowed to free-fall onto a fabric tile to simulate a sports turf surface and the readings tabulated below were recorded.

Drop No	Gravity Reading	Drop No	Gravity Reading
1	167	6	176
2	169	7	173
3	171	8	172
4	171	9	169
5	169	10	166

Signed for and on behalf of

SDi SIMON DEAKIN INSTRUMENTATION

Calibration Valid Until : 3/11/05

11. APPENDIX D

Before clustering players into subgroups, the ANOVA ($p < 0.05$) showed no showed no significant differences for running between conditions in terms of pressure.

Kinetic variables	SS	df	MS	SS	df	MS	F	p
F_z^{max} (BW)	0.00	1	0.00	5.15	151	0.03	0.0009	0.9756
$t\_F_z^{max}$ (s)	3279.25	1	3279.25	287684.25	151	1905.19	1.7212	0.1915
dF_z^{max} (BW s^{-1})*	6645.93	1	6645.93	446044.23	151	2953.94	2.2499	0.1357
$t\_dF_z^{max}$ (s)*	18.50	1	18.50	31357.03	151	207.66	0.0891	0.7657
A^{max} (mm^2)	84.32	1	84.32	11466.21	151	75.94	1.1105	0.2937
$\bar{A}$ (mm^2)	42.32	1	42.32	5209.96	151	34.50	1.2265	0.2698
P^{max} (BW mm^{-2})	0.01	1	0.01	0.79	151	0.01	1.3342	0.2499
t_P^{max} (s)	4904.10	1	4904.10	468181.44	151	3100.54	1.5817	0.2105
dP^{max} (BW mm^{-2} s^{-1})*	0.00	1	0.00	0.00	151	0.00	1.2531	0.2647
t_dP^{max} (s)*	152.11	1	152.11	198267.66	151	1313.03	0.1158	0.7341
P_R^{max} (BW mm^{-2})	0.00	1	0.00	0.62	151	0.00	0.0036	0.9522
$t\_P_R^{max}$ (s)	4588.86	1	4588.86	183733.70	151	1216.78	3.7713	0.0540
dP_R^{max} (BW mm^{-2} s^{-1})*	0.00	1	0.00	0.00	151	0.00	0.0677	0.7951
$t\_dP_R^{max}$ (s)*	1057.02	1	1057.02	29530.95	151	195.57	5.4048	0.0814
P_F^{max} (BW mm^{-2})	0.01	1	0.01	0.72	151	0.00	2.0444	0.1548
$t\_P_F^{max}$ (s)	1382.91	1	1382.91	95512.67	151	632.53	2.1863	0.1413
dP_F^{max} (BW mm^{-2} s^{-1})*	0.00	1	0.00	0.01	151	0.00	0.0242	0.8766
$t\_dP_F^{max}$ (s)*	80.89	1	80.89	144690.77	151	958.22	0.0844	0.7718

12. APPENDIX E: Copies of Papers Published from this project

Reprinted from: The Engineering of Sport 6, Volume 3: Developments for Innovation. E F Moritz & S Haake (Eds.), 2006, Springer, NY, USA. ISBN-10: 0-387-34680-5, p 255-260

An initial investigation of human-natural turf interaction in the laboratory

Victoria H. Stiles[1], Sharon J. Dixon[1] and Iain T. James[2]

1 University of Exeter, UK, v.h.stiles@exeter.ac.uk
2 Cranfield University, UK

Abstract. It is essential to provide high quality, safe and affordable sports surfaces in order to attain the health and social benefits from sports participation. Investment, construction and research into artificial sports surfaces have increased to meet this provision (Kolitzus, 1894; Nigg & Yeadon, 1987). Full provision cannot be met without natural turf surfaces, which also have an important role as greenspaces in the built environment. For improved access to sports facilities, there needs to be a significant improvement in the durability of natural turf surfaces and thus greater understanding of the human-natural sports surface interaction. Research into human interaction with natural surfaces is complicated by integrating natural soil media and sustaining turf growth in the laboratory environment. This study describes and provides data on methodology incorporating the biomechanical assessment of natural turf in the laboratory. Practicalities of using natural turf in the laboratory were overcome by using 10 portable plastic trays (0.57 m x 0.38 m x 0.08 m), turfed with ryegrass in a sand rootzone. Trays were positioned lengthways in the laboratory on non-slip matting (6 mm thick) to form a continuous runway and cover the force plate (AMTI, 960Hz). Ground reaction force (GRF) data were collected from two subjects wearing football boots (artificial turf/hard pitch design) for running, turning, and acceleration from rest. Mean GRF values compared well with the range of magnitudes presented in the literature for similar movements (Stucke, Baudzus & Baumann, 1984; Munro, Miller and Fuglevand, 1987; Miller, 1990) demonstrating that the incorporation of natural turf in the laboratory environment has been achieved successfully. Compared to running (subject 1, -0.41 ±0.06 BW; subject 2, -0.34 - ±0.04 BW), peak horizontal force increased for turning (subject 1, -0.50 ±0.06 BW; subject 2, -0.90 ±0.01 BW) and accelerating from rest (subject 1, -0.52 ±0.05 BW; subject 2, -0.44 ±0.09 BW), reflecting greater braking and propulsive requirements for the respective movements for both subjects. Peak vertical impact forces were 1.89 BW (±0.24) and 2.01 BW (±0.26) for subjects 1 and 2 respectively during running and 1.40 BW (±0.02) and 2.57 BW (±0.37) respectively during turning. To improve human-natural turf interaction, future studies will assess multiple subjects, movements, footwear and a range of natural turf conditions using the methodology developed here.

1 Introduction

Health and social benefits derived from sports and exercise participation are well documented (Department of Health, 2004). Affordable, safe and appropriate sports facilities make an important contribution to the promotion and attainment of a healthy nation. Participation in traditional sports such as hockey, football, tennis, rugby, cricket and lacrosse at school, club or elite level provide competitive opportunities to reap the health and social benefits of sports participation. These opportunities are much enhanced if the condition and provision of sports surfaces is appropriate.

Increased use of artificial surfaces in sport, particularly in tennis, hockey and to some extent football, has provided an all year round playing surface. Artifical surfaces are also less affected by adverse weather conditions, can require lower levels of maintenance and provide a smaller and more cost-effective facility tolerating regular multi-sport use compared to a natural surface (Kolitzus, 1984; Nigg & Yeadon, 1987; Cox, 2004). A natural sports surface is highly influenced by changes in the weather, does not tolerate a frequent multi-sport usage (problems of wear and degradation) and requires a larger area of ground to rotate pitch use. Artificial sports surfaces have made an important contribution to the provision of functional sports surfaces and increased sport participation. However the importance of maintaining natural turf sports surfaces is two-fold: it is crucial to protect greenspaces and playing fields in the built environment and to maintain the fundamental playing characteristics of sports such as football, rugby, golf, cricket and lacrosse.

Modification of hockey pitches that started in the 1970's from natural turf to artificial turf surfaces resulted in certain playing skill adaptations with a loss of some surface-related skills and an enhancement of other skills together with a faster-paced game (Spencer, Lawrence, Rechichi, Bishop, Dawson and Goodman, 2004). However, sports such as football are more reluctant to adapt the characteristics of their game to an artificial turf unless the surface allows complete replication of the characteristics of play (UEFA, 2005). The change in playing characteristics and reluctance encountered when switching from a traditional natural turf surface to artificial turf highlights the importance of maintaining the availability of natural turf sports surfaces. However, advancement in the construction and sustainability of natural sports surfaces is required if their provision is to be maintained for training and competitive use in sports.

There is a scarcity of research incorporating natural soil media into the biomechanics laboratory due to the logistical complications of integrating and sustaining turf growth in an un-natural environment. This fact is highlighted in a study that assessed studded footwear designed for use on grass with participants performing on artificial surfaces in a laboratory (Morag & Johnson, 2001). However, analysis of natural turf surfaces has been performed in the field to assess grip performance while performing cutting manoeuvres (Coyles, Lake & Patritti, 1998). Plantar pressures have also been assessed during soccer-specific movements in the field (Eils, Streyl, Linnenbecker, Thorwestern, Volker & Rosenbaum, 2004). However, the incorporation of natural turf in the laboratory is required in order to utilize biomechanical equipment that is either too sensitive or practically inappropriate to be used in an outdoor environment.

Advancement of natural sports turf engineering requires increased understanding of how turf responds to variations in human movement, ideally sports specific movement. Biomechanical assessment is required to provide input characteristics regarding the loading of natural turf. The first step in achieving the overall aim of a biomechanical analysis of sports specific movements on natural turf in the laboratory is to incorporate natural turf in the laboratory and collect initial data. The present study describes and provides data on methodology incorporating the biomechanical assessment of natural turf in the laboratory environment.

2 Methods

Ten portable plastic trays (0.57 m x 0.38 m x 0.08 m) were turfed with ryegrass in a sand rootzone (Fig. 1). Trays were positioned lengthways in the laboratory on non-slip matting (6 mm thick) to form a continuous runway and cover a force plate (AMTI, Massachussetts, 960 Hz). One tray was used to cover the force plate (force plate tray). All trays remained in place for the entire data collection period. A surrounding supportive runway of rubber matting and foam covered with an acrylic top-surface was constructed on either side of the turf runway for the safety of participants. Figure 2 illustrates the laboratory lay-out. Figure 3 presents a detailed picture of the laboratory set-up.

One female (Subject 1, S1) weighing 745 N and one male (Subject 2, S2) subject weighing 824 N both wearing football boots (size 10) of an artificial/hard pitch design performed football specific movements along the natural turf runway in the laboratory. Ten running trials at a speed of 3.83 $m.s^{-1}$ (±5%) were performed by each subject. Contact with the force plate was made with the right foot. A second movement involving turning, was performed on the force plate with the subject exiting the force plate pointing in the direction from which they had started the run-up. The third movement required the subject to start on the force plate and accelerate from rest using their preferred push-off leg. Three turning and accelerating from rest trials were performed by S1. Three turning trials and ten accelerating from rest trials were performed by S2. Approval for the collection of data from human participants was obtained from the School of Sport and Health Sciences, University of Exeter Ethics Committee.

A right-footed step was analysed for both the running and turning movements. Push-off during the accelerating from rest movement was analysed from the appropriate leg. Ground reaction force data (GRF) from the AMTI force plate (960 Hz) was collected from respective movement steps. In the case of the running and turning manoeuvres, data were analysed from steps that had been made without evidence of step alteration in order to meet the force plate. Where subjects failed to make contact with the plate in a natural style, data were discarded and the trial recollected.

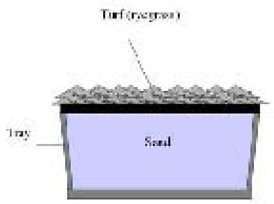


Fig. 1. Plastic tray turfed with ryegrass on a sand rootzone

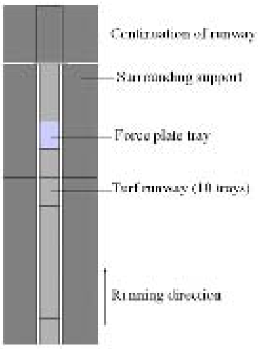


Fig. 2. Laboratory lay-out

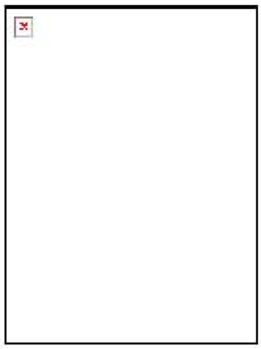


Fig. 3. Laboratory set-up

3 Results

Mean ground reaction force data for each subject performing each of the sports-specific movements (running, turning and accelerating from rest) are presented in Table 1.

Table 1. Mean ground reaction force results for subjects 1 and 2.

	Number of Trials	Peak Fz (BW)	Peak Fz Time (s)	Peak LR ($BW.s^{-1}$)	Average LR ($BW.s^{-1}$)	Peak Fy (BW)	Peak Fy Time (s)
Running (Peak Fy represents peak horizontal force during braking)							
S1	10	1.89 (±0.24)	0.03 (±0.01)	137.59 (±33.65)	64.85 (±17.25)	-0.41 (±0.06)	0.057 (±0.006)
S2	10	2.01 (±0.26)	0.03 (±0.01)	175.25 (±51.63)	63.97 (±21.64)	-0.34 (±0.04)	0.053 (±0.017)
Turning (Peak Fy represents peak horizontal force during braking)							
S1	3	1.40 (0.02)	0.078 (±0.018)	37.589 (±8.96)	18.633 (±5.1)	-0.50 (±0.06)	0.083 (±0.019)
S2	2	2.57 (±0.33)	0.043 (±0.004)	169.93 (±28.55)	60.02 (±1.55)	-0.90 (±0.01)	0.051 (±0.002)
Accelerating from rest (Peak Fy represents peak horizontal force during propulsion)							
S1	2	1.39 (±0.06)				-0.52 (±0.05)	
S2	10	1.45 (±0.18)				-0.44 (±0.09)	

4 Discussion

The present study collected data from two subjects performing sports specific movements on a natural turf surface in the laboratory. Peak impact forces found in the present study (1.89 BW and 2.01 BW) compared well to those presented in the literature. Running at a speed of 3.75 $m.s^{-1}$ typically yields peak vertical impact forces of approximately 1.86 BW (Munro et al., 1987). Subjects in the present study yielded peak horizontal braking forces representing 41% and 34% of their body-weight, magnitudes that are also supported by values presented in the literature (Miller, 1990).

In the present study although a fewer number of trials were collected for the turning movement, subjects yielded higher magnitudes of peak braking force during turning (S1, -0.50 ±0.06 BW; S2, -0.90 ±0.01 BW) compared to their running step (S1, -0.41 ±0.06 BW; -0.34 ±0.04 BW). This expected result reflects a higher braking force requirement for turning compared to running. It is suggested in the present and future studies that ground reaction force data derived from turning and accelerating movements may provide useful implications for turf wear and thus turf design in the future.

Subjects in the present study, when accelerating from rest yielded propulsive horizontal force components of approximately half their bodyweight. Time histories in the literature depicting peak horizontal propulsive forces for a similar movement on cinder and artificial turf surfaces yield higher magnitudes of approximately -0.64 BW and -0.79 BW respectively (Stucke et al., 1984). Differences in values yielded

Biomechanical Response to Variations in Natural Turf Surfaces during Running and Turning

V.H. Stiles [1], S.J. Dixon [1], I.N. Guisasola [2] and I.T. James [2]

[1] *School of Sport and Health Sciences, University of Exeter, UK*
[2] *Cranfield Centre for Sports Surfaces, Cranfield University, UK*
V.H.Stiles@exeter.ac.uk

ABSTRACT

The health and social benefits from sports participation are more easily achieved if sports surface provisions are safe, affordable and of a high quality. Investment, construction and research into artificial sports surfaces have increased to meet this provision (Kolitzus, 1984; Nigg & Yeadon, 1987). However, full provision cannot be met without natural turf surfaces, which also have an important role as green spaces in the built environment. If natural turf surfaces are to help meet the provision of sports surfaces in the UK, advancement in the construction and sustainability of natural turf surface design is required. Despite natural turf being a common playing surface for popular sports such as soccer, rugby and cricket, few biomechanical studies have been performed using natural turf conditions. This study describes a biomechanical approach to investigating human response to changes in natural turf playing surface. Three different rootzone conditions (clay, sandy and rootzone) were constructed in portable plastic trays (0.60 m x 0.40 m x 0.08 m) and turfed with ryegrass. Each turf condition was made up of 45 trays. Trays were positioned in the laboratory on non-slip matting (6 mm thick) to form a continuous runway and cover the force plate (AMTI, 960Hz). Ground reaction force (GRF) data were collected from eight subjects wearing football boots (studded natural turf design) for running and turning. Mechanical measures of surface hardness (Clegg Hammer) and shear were taken before and after subject testing. Moisture content was also measured prior to testing.

Whilst significant differences in peak active force and peak rate of loading across surface conditions were found during running, ground reaction force parameters during turning revealed similar rankings of condition as mechanical rankings of condition using measures of shear. The present study therefore suggests that turning provides more scope to study the relationship between the mechanical properties of the turf and biomechanical measures of human response in pursuit of engineering a more sustainable natural turf sports surface.

INTRODUCTION

The Department of Health in the United Kingdom recognizes that participation in sport and exercise activities yields important health and social benefits for the individual and reduced dependence on community primary care health provisions (Department of Health, 2004). Promotion and attainment of a healthy nation can be aided by appropriate sports facilities that are affordable and safe. Benefits to health and society can be gained via participation in traditional, competitive sports such as hockey, football, tennis, rugby, cricket and lacrosse at school, club and elite level. However, it is important that in order for these activities to operate with relative ease, thus reaping the health advantages, the condition and provision of sports surfaces are appropriate at a variety of sporting levels.

Sports such as tennis, hockey and to some extent soccer have benefited from incorporating artificial surfaces into the game as they provide year round playing opportunity. The influence of adverse weather conditions on a surface's playing ability is also less affected when playing on artificial surfaces compared to natural turf. An artificial turf surface also requires a lower level of maintenance, can be constructed within a relatively small space and can tolerate regular multi-sport use compared to a natural turf surface (Kolitzus, 1984; Nigg & Yeadon, 1987; Cox, 2003). Artificial sports surfaces have made an important contribution to the provision of functional sports surfaces and increased sport participation. By comparison, a natural turf surface requires a larger area of ground providing the scope to rotate pitch usage as a method of surface regeneration, does not withstand the rigors of frequent multi-sport use and playing properties are considerably influenced by changes in the weather. There is a need however to continue to develop natural turf surfaces, the reasons for which are two-fold; the protection of green spaces and playing fields in the built environment is crucial and the preservation of fundamental playing characteristics for sports such as soccer, rugby, golf, cricket and lacrosse is paramount.

It may be considered that the game of hockey has benefited from its move away from natural turf onto artificial pitches that started in the 1970's. Modification of the hockey pitch changed the traditional playing characteristics of the game, resulting in certain surface-related skills being lost, but replaced with heightened reaction and agility skills encountered as a result of playing on a faster surface (Spencer, Lawrence, Rechichi, Bishop, Dawson and Goodman, 2004). The move from natural turf surfaces to artificial surfaces for sports such as soccer appears to be somewhat more reluctant due to the risk of modifying playing characteristics of the game (UEFA, 2005). Thus, in order for sports to maintain these playing characteristics, they must remain on natural turf surfaces, placing a greater demand on natural turf surface provision. Surface provision for training and competitive use for sports such as soccer and rugby can only be met if advancement is made in the construction and sustainability of natural turf surfaces.

Despite natural turf being a common playing surface for popular sports such as soccer, rugby and cricket, few biomechanical studies have been performed using natural turf conditions. It is suggested that logistical complications of incorporating a natural soil media in the biomechanics laboratory has inhibited progress on understanding how wear and tear of a natural turf surface is achieved during sporting activity and how humans respond to changes in natural turf properties from the biomechanical perspectives of injury and performance. Some analysis of natural turf properties has been achieved in the field for example during the assessment of traction performance during cutting manoeuvres (Coyles, Lake & Patritti, 1998) and plantar pressures underfoot during sports specific movements (Eils, Streyl, Linnenbecker, Thorwestern, Volker & Rosenbaum, 2004). However, incorporation of natural turf in the laboratory is important in order to be able to use biomechanical equipment that is either too sensitive or practically inappropriate to be used in an outdoor environment. Typical running, turning and accelerating ground reaction force profiles have previously been derived from subjects performing sports specific movements on a natural turf surface in the laboratory (Stiles, Dixon & James, 2006). This work forms an initial benchmark for biomechanical analysis of natural turf however one that requires further support and validation from more sophisticated studies. It is suggested by the present paper that advancement in construction and sustainability aspects of natural turf surface design requires research that uses a two-pronged approach incorporating assessment of mechanical and biomechanical properties of the surface using multiple subjects.

Advancement of natural sports turf engineering requires increased understanding of how turf responds to variations in sports specific human movement. Ground reaction force data, specifically peak impact force (vertical), peak rate of loading (vertical), peak active force (vertical), peak braking force (anterior-posterior), peak propulsive force (anterior-posterior), have been used extensively in biomechanical research to characterize the ground contact phase during human movement and to monitor human response to changes in material properties underfoot. Assessment of mechanical properties of a surface has frequently used devices such as the Clegg Hammer yielding a measure of 'peak deceleration (g)' to characterize and monitor natural surface hardness (Clegg, 1976; Holmes & Bell, 1986). The bulk shear strength of turf can be quantified using a cruciform Shear Vane, which is used *in situ* to measure un-drained shear strength by the rotation of a cruciform vane to soil failure (τ, in kN m^{-2}; BS1377-9, 1990). Soil moisture content is a key factor in soil strength and can be measured using a dielectric probe (e.g. a Theta Probe, Delta-T, Cambridge) that determines the volume of water per unit volume of soil as a percentage (vol%), (Gaskin & Miller, 1996).

The present study aimed to reveal how measures of ground reaction force change in relation to variations in natural turf properties. In addition, the relationship between biomechanical measures of a surface using human participants and mechanical measures of natural turf characterization was investigated. It was hypothesized that a surface with comparatively the highest mechanical hardness, lowest moisture content and highest shear strength would yield the highest peak impact forces and peak rates of loading compared to a turf surface with the lowest mechanical measure of hardness, moisture content and shear strength.

METHODS

Ten portable plastic trays (0.60 m x 0.40 m x 0.08 m) were turfed with ryegrass in three different soils of a 0.07 m depth (Table 1). The 'clay' condition was typical of heavy clay football pitches, the high sand 'rootzone' condition was typical of modern, elite natural surfaces and the 'sandy' condition provided an intermediate sand-content condition. Trays were positioned sideways in the biomechanics laboratory on non-slip matting (6 mm thick) to form a continuous runway of one surface condition (Figure 1). Within the continuous runway, the tray on the force plate (AMTI, Massachusetts, 960 Hz) was positioned lengthways with additional trays either side providing a safe area for subjects to run on. Care was taken to make sure that the sides of the force plate tray did not overhang the area of the force plate. Trays containing the other two turf conditions were positioned inside the laboratory at the same time as the condition constructing the runway and thus being tested. Surface conditions were rotated during a subject testing session as required to construct the testing runway. Before testing, the trays of turf located in the laboratory were mowed to a length of 29 mm.

Table 1. Turf Conditions

	Clay (%)	Silt (%)	Sand (%)	Dry Bulk Density (kg/m3)
Clay Loam	27	44	29	1294
Sandy Loam	13	28	59	1517
Rootzone	1	1	98	1736

Eight male volunteers were recruited and consented to be participants in the study. Approval for the collection of data from human participants was obtained from the School of Sport and Health Sciences, University of Exeter Ethics Committee. Each participant was either a soccer or rugby player of a university or club standard and regularly participated in training and match playing sessions on a natural turf surface whilst wearing studded footwear. Participants were assigned standard metal studded soccer boots in their size with conical stud design (UK sizes, 10, 11 & 12). All participants wore the same model of boot. Participants were required to visit the laboratory on two separate occasions to study two different sports specific movements; running and turning. During a test session, boot-shod participants were familiarized with the session's sports specific movement on the runway whilst a spare tray of turf was positioned on the force plate. For running, a constant speed of 3.83 $m.s^{-1}$ was required between two sets of photocells set 1 m away from the center line of the force plate (2 m distance between photocell sets). Participants were required to make a right-footed contact with the force plate during each trial without targeting the plate. Where subjects failed to make contact with the plate in a natural style, data were discarded and the trial recollected.

For turning, participants were required to place their right foot on the force plate at a 90-degree angle to the direction of movement and push off to change direction and return along their line of entry to their starting position. After familiarization, the standard turning movement became second nature as participants were asked to repeatedly perform the movement. Timing gates were not used to monitor entry speed to the force plate as preliminary tests demonstrated that the photocells beams were disrupted with quick repetition by arm action during preparation to the turn, the turn itself and exiting the force plate. A turning trial was considered successful by two experimenters who subjectively assessed whether there was visual or audio evidence of changes in the time take to perform the movement, disruption to the step pattern or whether the expected pattern of metronomic sound created by steps on the turf was considered irregular.

Ground reaction force data were collected from 10 successful trials for both running and turning movements for each subject on each type of turf condition (Session 1: 10 running trials on each condition; Session 2: 10 turning trials on each condition; total of 30 successful trials per session). After 10 trials on one condition, the force plate tray was removed and preserved for shear strength analysis. Each force plate tray was therefore unique to a subject and the sports specific movement. If not considerably damaged, all other trays of turf were kept for future test sessions in order to create another runway for another subject on another day for one of the three conditions. All trays of turf were relocated outside overnight and on occasion rested with appropriate water maintenance for one or two days depending on laboratory test requirements and obvious turf damage.

Measures of surface hardness (Peak 'g') using a Clegg Hammer were performed immediately before and after the subject testing session on the force plate tray. Three Clegg Hammer test procedures were performed on the test tray in a diagonal formation; corner one (bottom left), centre, corner two (top right). The mean of the three tests was taken to represent surface hardness for each tray and was calculated for each surface condition under each movement. Standard deviations are used to indicate the reliability of tray hardness within each surface condition. Volumetric soil moisture content was measured immediately prior to the test session for all trays in the runway using a Theta Probe. Surface mean soil moisture content was calculated and was presented for each movement. From these values, the degree of saturation was calculated as a percentage of the saturation moisture content (maximum volume of voids in the soil). Shear strength of the force plate tray was quantified prior to and after the subject testing session using a shear vane inserted to a depth of 33 mm. Shear strength is presented in kPa. Surface mean soil shear strength is presented for each movement.

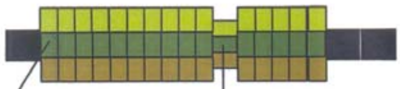


Fig. 1. Laboratory lay-out

RESULTS

Group mean ground reaction force data for each movement together with mechanical test averages are presented in Tables 2 and 3.

Table 2. Running: mechanical and ground reaction force means (*sig p<0.05). BW = bodyweights, LR = loading rate

	Clay	Sandy	Rootzone
Peak active force (BW) ***sig**	2.53 (±0.6)	2.47 (±0.5)	2.50 (±0.5)
Peak LR ($BW.s^{-1}$) ***sig**	84.67 (±22.9)	96.74 (±29.1)	101.48 (±23.3)
Peak braking force (BW)	-0.21 (±0.07)	-0.22 (±0.09)	-0.22 (±0.08)
Average braking LR ($BW.s^{-1}$)	3.81 (±1.3)	3.93 (±2.5)	3.80 (±1.0)
Hardness before (peak g)	59.47 (±15.91)	67.13 (±9.06)	58.34 (±5.75)
Hardness after (peak g)	70.47 (±13.76)	72.62 (±11.83)	64.30 (±9.57)
Difference in Hardness (peak g)	+ 11.00	+ 5.49	+ 5.96
Shear before (kPa)	24.56 (±4.98)	23.48 (±2.01)	21.74 (±1.16)
Shear after (kPa)	24.99 (±4.58)	25.15 (±2.35)	22.32 (±2.19)
Difference in Shear (kPa)	+ 0.43	+1.67	+ 0.58
Moisture at time of testing (vol%)	30.96 (±3.82)	28.67 (±2.18)	31.63 (±3.65)

Table 3. Turning: mechanical and ground reaction force means. BW = bodyweights, LR = loading rate

	Clay	Sandy	Rootzone
Peak impact force (BW)	2.32 (±0.2)	2.25 (±0.2)	2.33 (±0.2)
Pk LR ($BW.s^{-1}$)	110.31 (±25.6)	99.57 (±25.0)	97.89 (±16.15)
Peak braking force (BW)	-0.883 (±0.06)	-0.887 (±0.07)	-0.875 (±0.06)
Average braking LR ($BW.s^{-1}$)	15.86 (±3.2)	15.36 (±3.4)	14.13 (±1.8)
Hardness before (peak g)	61.81 (±21.33)	57.38 (±13.53)	57.85 (±13.36)
Hardness after (peak g)	73.34 (±17.18)	59.47 (±13.06)	53.00 (±9.12)
Difference in Hardness (peak g)	+ 11.53	+ 2.09	- 4.85
Shear before (kPa)	27.53 (±2.74)	24.51 (±2.44)	21.66 (±1.29)
Shear after (kPa)	32.90 (±3.71)	28.07 (±2.49)	23.61 (±2.27)
Difference in Shear (kPa)	+ 5.37	+ 3.56	+ 1.95
Moisture at time of testing (vol%)	29.45 (±3.18)	30.78 (±1.93)	32.06 (±3.10)

DISCUSSION

The present study collected data from eight subjects performing running and turning movements on three natural turf surfaces in the laboratory. Turf wear and soil deformation has been measured using standard techniques for natural turf sports surfaces (BS EN 12231:2003 & BS EN 14954:2005). During the running trials, compared to the other two surfaces, the sandy condition was hardest prior to testing. Peak rate of loading that occurred during the impact phase of ground contact and thus is used as an indicator of surface cushioning was only second highest on this surface. Peak rate of loading was significantly lower on the clay surface that according to mechanical hardness was joint-lowest with the rootzone condition. For running, peak active force that represents the propulsive phase of ground contact was significantly higher on clay compared to the other two surfaces.

For turning, the clay surface was hardest compared to the rootzone and sandy conditions. Little difference was found with changes in condition using peak vertical impact force or peak vertical rate of loading although peak rate of loading was higher on clay compared to sandy and rootzone. Average horizontal rate of loading did however rank surfaces in a similar manner to rankings derived from measures of shear before and after subject testing. Shear and average horizontal rate of loading were lowest for rootzone. The shear value for rootzone indicates a lower resistance to material failure compared to the other two conditions. Values for shear and horizontal rate of loading were higher on sandy with clay yielding the highest values. Correlations (Pearson) however were not significant. Previous research that incorporated natural turf into the biomechanics laboratory found that larger horizontal braking forces were yielded for the turning condition compared to running and as such the turning movement may have implications for turf degradation (Stiles, Dixon & James, 2006).

CONCLUSIONS

Although in the initial stages, a relationship between turf condition hardness, shear strength and horizontal rates of loading appears to be apparent in the present study using the turning movement. Data from the present study demonstrate that changes in mechanical properties of turf are more apparent using biomechanical methods of assessment when participants are performing the movement of turning compared to running. It is therefore suggested that the turning movement provides more scope to study the relationship between the mechanical properties of turf and biomechanical measures of human response. Future research will focus on analysing additional measures of human response using three-dimensional kinematic analysis and pressure measurements under the foot in pursuit of engineering a more sustainable natural turf sports surface.

REFERENCES

BS1377-9:1990. 'Soils for civil engineering puposes – Part 9: in-situ tests,' *Brtish Standards Institute*, London. ISBN 0 580 18242 8.

Clegg, B. 1976, 'An impact testing device for in situ base course evaluation,' *Australian Road Research Bureau Proceedings*, 8, 1-6

Cox, A.L. 2003, 'Test methods for assessing the performance of sports surfaces,' in *Sports Surfaces* ed. B.M. Nigg, G.K. Cole & D.J. Stefanyshyn, University of Calgary, 269-291.

Department of Health 2004, At least five a week – evidence on the impact of physical activity and its relationship to health. *Department of Health, Physical Activity, Health Improvement and Prevention.*

Gaskin, G. J., Miller, J. D. 1996, 'Measurement of soil water content using a simplified impedance measuring technique,' *Journal of Agricultural Engineering Research*. Vol. 63, pp. 53-160.

Holmes, G., Bell, M. J. 1986, 'A pilot study of the playing quality of football pitches,' *Journal of the Sports Turf Research Institute*, vol. 63, pp. 74-91.

Kolitzus, H.J. 1984, 'Functional standards for playing surfaces in *Sports Shoes and Playing Surfaces: Biomechanical Properties*, ed. E.C. Frederick, Human Kinetics Publishers Inc: Champaign, IL, 98-118.

Nigg, B.M. and Yeadon, M.R. 1987, 'Biomechanical aspects of playing surfaces,' *Journal of Sports Sciences*, vol. 5, pp. 117-145.

Spencer, M., Lawrence, S., Rechichi, S., Bishop, D., Dawson, B. and Goodman, C. 2004, 'Time motion analysis of elite field hockey, with special reference to repeated-sprint activity,' *Journal of Sports Sciences*, vol. 22, pp. 843-850.

Stiles, V.H., Dixon, S.J., & James, I.T. 2006, 'An Initial Investigation of Human-Natural Turf Interaction in the Laboratory,' in *The Engineering of Sport* Vol. 3 ed. E.F Moritz & S. Haake, New York, Springer, 255 - 260.

UEFA, Turf first in the Netherlands, (2005) Retrieved from www.uefa.com 06/10/05.

Acknowledgements

The authors gratefully acknowledge the funding of this research by the Engineering and Physical Sciences Research Council, UK under project EP/C512243/1(P).

Proceedings of 7th ISEA CONFERENCE 2008
Biarritz, June 2-6, 2008

Kinematic Response to Variations in Natural Turf During Running

Stiles, V. H. *1, Dixon, S.D.1, Guisasola, I.N.2, James, I.T2

(1) : *School of Sport and Health Sciences, University of Exeter, Exeter, EX1 2LU, UK
+44 (0)1392 262885 / +44 (0)1392 264726
E-mail : {v.h.stiles; s.j.dixon} @exeter.ac.uk

(2) : Cranfield Centre for Sports Surfaces, Cranfield University, Bedford, MK43 0AL, UK
+44 (0)1234 750111 /+44 (0)1234 752971
E-mail : {i.t.james; i.guisasola.s05} @cranfield.ac.uk

Topics: Biomechanics

Abstract: Important health and social benefits can be gained from participation in sports and exercise. Appropriate surface provision that aids sports participation, cannot be met by artificial surfaces alone – it requires natural turf surfaces to be utilised. Considerable improvement in the durability of natural turf surfaces and thus, a greater understanding of the human-natural sports surface interaction is required. Ground reaction force data have been used to help quantify how human participants respond to changes in natural turf properties during running and turning. A kinematic analysis would further this understanding. This EPSRC/UK funded study analyses kinematic response to variations in natural turf during running. Three different rootzone conditions (clay, sandy and rootzone) were constructed in portable plastic trays (0.60 m x 0.40 m x 0.08 m) and turfed with ryegrass. Trays were positioned in the laboratory on non-slip matting (6 mm thick) to form a continuous runway. Three-dimensional kinematic data (Vicon Peak, automatic, opto-electronic system 120 Hz) were collected for nine subjects wearing football boots (studded natural turf design) during running ($3.83 m.s^{-1}$). Group mean data for initial and peak ankle and knee angles and peak joint angular velocities were statistically compared using an analysis of variance with repeated measures (RMANOVA, $p<0.05$). Mechanical measures of surface hardness (Clegg Hammer) and shear were taken before and after subject testing and assessed using a paired t-test ($p<0.05$). Moisture content was also assessed. Kinematic data were found to be representative of typical running values presented in the literature. While mechanical measures revealed that natural turf conditions were not identical, changes in surface did not yield any significant kinematic differences. The consistent production of ankle and knee joint kinematics with changes in mechanical surface properties could suggest that humans prefer to maintain similar geometries when running on a variety of natural turf surfaces. Alternatively, the mechanical properties of the natural turf conditions may not have been sufficiently different to elicit changes in human response during running.

Key words: kinematics, natural turf, running

1- Introduction

The World Health Organisation (WHO) and Department of Health (DoH) in the United Kingdom recognizes that participation in sport and exercise activities yields important health and social benefits for the individual and reduced dependence on community primary care health provisions (WHO, 2003 ; DoH, 2004). Promotion and attainment of a healthy nation can be aided by appropriate sports facilities that are affordable and safe. Benefits to health and society can be gained via participation in traditional, competitive sports such as hockey, football, tennis, rugby, cricket and lacrosse at school, club and elite level. However, it is important that in order for these activities to operate with relative ease, thus reaping the health advantages, the condition and provision of sports surfaces are appropriate at a variety of sporting levels.

Sports such as tennis, hockey and to some extent soccer have benefited from incorporating artificial surfaces into the game as they provide year round playing opportunity. The influence of adverse weather conditions on a surface's playing ability is also less affected when playing on artificial surfaces compared to natural turf. An artificial turf surface also requires a lower level of maintenance, can be constructed within a relatively small space and can tolerate regular multi-sport use compared to a natural turf surface (Kolitzus, 1984; Nigg & Yeadon, 1987). Artificial sports surfaces have made an important contribution to the provision of functional sports surfaces and increased sport participation. By comparison, a natural turf surface requires a larger area of ground providing the scope to rotate pitch usage as a method of surface regeneration, does not withstand the rigors of frequent multi-sport use and playing properties are considerably influenced by changes in the weather. There is a need however to continue to develop natural turf surfaces, the reasons for which are two-fold; the protection of green spaces and playing fields in the built environment is crucial and the preservation of fundamental playing characteristics for sports such as soccer, rugby, golf, cricket and lacrosse is paramount.

It may be considered that the game of hockey has benefited from its move away from natural turf onto artificial pitches that started in the 1970's. Modification of the hockey pitch changed the traditional playing characteristics of the game, resulting in certain surface-related skills being lost, but replaced with heightened reaction and agility skills encountered as a result of playing on a faster surface (Spencer, Lawrence, Rechichi, Bishop, Dawson and Goodman, 2004). The move from natural turf surfaces to artificial surfaces for sports such as soccer appears to be somewhat more reluctant due to the risk of modifying playing characteristics of the game (UEFA, 2005). Thus, in order for sports to maintain these playing characteristics, they must remain on natural turf surfaces, placing a greater demand on natural turf surface provision. Surface provision for training and competitive use for sports such as soccer and rugby can only be met if advancement is made in the construction and sustainability of natural turf surfaces.

Despite natural turf being a common playing surface for popular sports such as soccer, rugby and cricket, few biomechanical studies have been performed using natural turf conditions. It is suggested that logistical complications of incorporating a natural soil media in the biomechanics laboratory have inhibited progress on understanding how wear and tear of a natural turf surface is achieved during sporting activity and how humans respond to changes in natural turf properties from the biomechanical perspectives of injury and performance. Some analysis of natural turf properties has been achieved in the field for example during the assessment of traction performance during cutting maneuvers (Coyles, Lake & Patritti, 1998) and plantar pressures underfoot during sports specific movements (Eils, Streyl, Linnenbecker, Thorwestern, Volker & Rosenbaum, 2004). However, incorporation of natural turf in the laboratory is important in order to be able to use biomechanical equipment that is either too sensitive or practically inappropriate to be used in an outdoor environment. Typical running, turning and accelerating ground reaction force profiles have previously been derived from subjects performing sports specific movements on a natural turf surface in the laboratory (Stiles, Dixon & James, 2006). This work forms an initial benchmark for biomechanical analysis of natural turf however one that requires further support and validation from more sophisticated studies. Recently, biomechanical response to variations in natural turf surface quantified using ground reaction force data derived from multiple participants during running and turning in the laboratory has been presented (Stiles, Dixon, Guisasola & James, 2007). Analysis of ground reaction force data, whilst useful, only quantifies one aspect of the human's complex ability to respond to changes in turf condition. Numerous studies have used a kinematic analysis to understand how humans respond and alter their lower limb geometry when running with different mechanical properties of shoes and surfaces underfoot (Bobbert, Yeadon & Nigg, 1992; De Wit, De Clercq & Aerts, 2000 ; Dixon, Collop & Batt, 2000). For example, an increase in initial knee flexion (cushioning flexion) during running has been yielded as a compensatory adjustment when contacting a surface with increased stiffness (Bobbert, et al., 1992). In addition, a flatter foot (reduced dorsi-flexion) has been observed for barefoot compared with shod running. Limited research is available however that reports kinematic data for participants running on natural turf surfaces. The present study proposes analysis of kinematic response (initial and peak ankle and knee angles and peak angular velocities) to variations in natural turf during running in order to characterise patterns of human movement when running on natural turf. Initial indications of how humans adjust their geometry when running on a variety of natural turf surfaces can also be studied.

Variations in natural turf can be constructed via modifying the material properties of the rootzone. Variations in turf construction in-situ can be quantified using mechanical tests. Assessment of mechanical properties of a surface has frequently used devices such as the Clegg Hammer yielding a measure of 'peak deceleration (g)' to characterize and monitor natural surface hardness (Clegg, 1976; Holmes & Bell, 1986). The bulk shear strength of turf can be quantified using a cruciform Shear Vane, which is used *in situ* to measure un-drained shear strength by the rotation of a cruciform vane to soil failure (τ, in kN m^{-2}; BS1377-9, 1990). Soil moisture content is a key factor in soil strength and can be measured using a dielectric probe (e.g. a Theta Probe, Delta-T, Cambridge) that determines the volume of water per unit volume of soil as a percentage (vol%), (Gaskin & Miller, 1996).

In keeping with literature evidence regarding changes in the shoe-surface interface, it was hypothesized that the turf condition with the highest mechanical hardness, lowest moisture content and highest shear strength would yield increased magnitudes of initial knee flexion (cushioning flexion) and reduced ankle dorsi-flexion compared to a turf surface with the lowest mechanical measure of hardness, moisture content and shear strength. The additional kinematic variables of peak knee flexion, peak ankle angle and peak ankle and knee angular velocities are assessed to monitor whether humans move consistently when running on a variety of natural turf surfaces in the laboratory.

2- Methods

Ten portable plastic trays (0.60 m x 0.40 m x 0.08 m) were turfed with ryegrass in three different soils of a 0.07 m depth (Table 1). The 'clay' condition was typical of heavy clay football pitches, the high sand 'rootzone' condition was typical of modern, elite natural surfaces and the 'sandy' condition provided an intermediate sand-content condition. Trays were positioned sideways in the biomechanics laboratory on non-slip matting (6 mm thick) to form a continuous runway of one surface condition (Figure 1). Within the continuous runway, the target tray upon which participants were required to contact during running was positioned lengthways with additional trays on either side providing a safe area for subjects to pass over. Trays containing the other two turf conditions were positioned inside the laboratory at the same time as the condition constructing the runway and thus being tested. Surface conditions were rotated during a subject testing session as required to construct the testing runway. Before testing, the trays of turf located in the laboratory were mowed to a length of 29 mm.

	Clay (%)	Silt (%)	Sand (%)	Dry Bulk Density (kg/m3)
Clay Loam	27	44	29	1294
Sandy Loam	13	28	59	1517
Rootzone	1	1	98	1736

Table 1. Turf Conditions

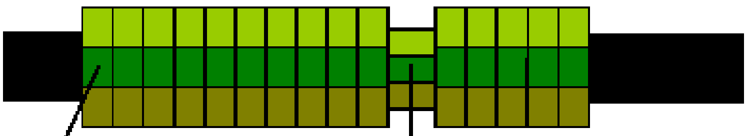


Figure. 1. Laboratory lay-out

Nine male volunteers were recruited and consented to be participants in the study. Approval for the collection of data from human participants was obtained from the School of Sport and Health Sciences, University of Exeter Ethics Committee. Each participant was either a soccer or rugby player of a university or club standard and regularly participated in training and match playing sessions on a natural turf surface whilst wearing studded footwear. Participants were assigned standard metal studded soccer boots in their size (UK sizes, 10, 11 & 12). All participants wore the same model of boot. Participants were required to visit the laboratory on one occasion to complete running trials on all three test surfaces. During a test session, boot-shod participants were familiarized with the running movement on the runway whilst a spare tray of turf was positioned in the target area of the runway. A constant running speed of 3.83 $m.s^{-1}$ was required between two sets of photocells set 1 m away from the center line of the target tray (2 m distance between photocell sets). Participants were required to make a right-footed contact with the target tray during each trial without adjusting their running stride and rhythm. Starting positions were marked out in the laboratory during the familiarisation trials to assist participants in making contact with the tray without adjusting their running action. Where subjects failed to make contact with the target tray in a natural style or run within the specified speed range, data were discarded and the trial recollected.

Kinematic data were collected (Vicon Peak, automatic, opto-electronic system 120 Hz) from 10 successful running trials for each subject on each type of turf condition (total of 30 successful trials per session). After 10 trials on one condition, the target tray was removed and preserved for shear strength analysis. Each target tray was therefore unique to a subject. If not considerably damaged, all other trays of turf were kept for future test sessions in order to create another runway for another subject on another day for one of the three conditions. All trays of turf were relocated outside overnight and on occasion rested with appropriate water maintenance for one or two days depending on laboratory test requirements and obvious turf damage. Three dimensional initial (frame immediately prior to ground contact) and peak ankle and knee joint angles (during stance) were assessed together with peak joint angular velocities (during stance) and respective times of occurrence relative to the start of ground contact. Kinematic data were filtered using a quintic spline, (Peak Performance default optimal smoothing technique using 5th degree quintic polynomials; Woltring, 1985). A combined and adapted version of joint coordinate systems presented by Soutas-Little, Beavis, Verstraete and Markus, (1987) and Vaughan, Davis and O'Connor, (1992) was employed to monitor joint movement at the ankle and knee. Joint angles were referenced to a relaxed standing position. A positive ankle angle represents dorsi-flexion.

Measures of surface hardness (Peak 'g') using a Clegg Hammer were performed immediately before and after the subject testing session on the target tray. Three Clegg Hammer test procedures were performed on the test tray in a diagonal formation; corner one (bottom left), center, corner two (top right). The mean of the three tests was taken to represent surface hardness for each tray and was calculated for each surface condition under each movement. Standard deviations are used to indicate the reliability of tray hardness within each surface condition. Volumetric soil moisture content was measured immediately prior to the test session for all trays in the runway using a Theta Probe. Surface mean soil moisture content was calculated and was presented for each movement. From these values, the degree of saturation was calculated as a percentage of the saturation moisture content (maximum volume of voids in the soil). Shear strength of the target tray was quantified prior to and after the subject testing session using a shear vane inserted to a depth of 33 mm. Shear strength is presented in kPa. Surface mean soil shear strength is presented for each movement.

3- Results

Group mean data for nine subjects running on three different natural turf surfaces are presented in table 2 together with mechanical test results. Initial ankle and knee joint angles remain at similar magnitudes with changes in surface. Peak ankle and knee joint angles are also similar across conditions. Ankle range of movement (ROM) appears to be lower on the rootzone surface compared to the clay condition however this difference was not significant ($p>0.05$). Peak ankle and knee angular velocities were similar across turf conditions.

Mechanical measures of hardness reveal that the rootzone condition possessed similar magnitudes of hardness (58.34 peak g, ±5.75) compared to the clay condition (59.47 peak g, ±15.91) prior to biomechanical testing. However, the rootzone condition compared to both clay and sandy conditions possessed significantly lower levels of hardness (64.30 peak g, ±9.67 compared to 70.47 peak g ±13.76 and 72.62 peak g, ± 11.83 respectively) after participant test sessions ($p<0.05$). Measures of shear demonstrate that the rootzone condition consistently possessed lower resistance to shear failure before and after (significant, $p<0.05$) participant test sessions compared to clay and sandy conditions.

	Clay	Sandy	Rootzone
Kinematic Data			
Initial ankle angle (degs)	0.62 (±8.4)	1.18 (7.75)	2.36 (±7.9)
Peak ankle angle (degs)	14.22 (±8.5)	14.01 (±8.65)	13.90 (±8.6)
Peak ankle angle time of occurrence (s)	0.149 (±0.02)	0.147 (±0.01)	0.147 (±0.02)
Ankle ROM (deg)	13.60 (±3.9)	12.83 (±3.5)	11.54 (±3.1)
Initial knee angle (degs)	10.53 (±6.0)	10.60 (±4.6)	10.89 (±4.1)
Peak knee angle (degs)	35.30 (±6.0)	34.86 (±3.9)	34.64 (±4.9)
Peak knee angle time of occurrence (s)	0.115 (±0.01)	0.114 (±0.01)	0.118 (±0.01)
Knee ROM (degs)	24.76 (±5.5)	24.26 (±5.1)	23.75 (±6.0
Peak ankle angular velocity ($rad.s^{-1}$)	4.25 (±0.4)	4.14 (±0.5)	4.04 (±0.6)
Peak ankle angular velocity time of occurrence (s)	0.095 (±0.011)	0.092 (±0.014)	0.099 (±0.014)
Peak knee angular velocity ($rad.s^{-1}$)	5.34 (±1.2)	5.42 (±1.0)	5.43 (±0.9)
Peak knee angular velocity time of occurrence (s)	0.054 (±0.017)	0.051 (±0.010)	0.060 (±0.013)
Mechanical Data			
Hardness before (peak g)	59.47 (±15.91)	67.13 (±9.06)	58.34 (±5.75)
Hardness after (peak g)	70.47 (±13.76)	72.62 (±11.83)	* 64.30 (±9.57)
Difference in Hardness (peak g)	+ 11.00	+ 5.49	+ 5.96
Shear before (kPa)	24.56 (±4.98)	23.48 (±2.01)	21.74 (±1.16)
Shear after (kPa)	24.99 (±4.58)	25.15 (±2.35)	* 22.32 (±2.19)

Table 2. Kinematic and mechanical mean data (*sig $p<0.05$ compared to the clay condition)

4- Discussion

The present study collected kinematics data from nine participants performing running on three natural turf surfaces in the biomechanics laboratory. Kinematic running data from the present study demonstrate that typical magnitudes of knee and ankle variables have been yielded from participants running on a variety of natural turf surfaces in the biomechanics laboratory. These values compare well to those presented in the running literature (Bobbert et al., 1992) and therefore the dynamics of running have been satisfactorily reproduced. Initial indications of how humans adjust their geometry when running on a variety of natural turf surfaces have also been studied.

Turf wear and soil deformation have been measured using standard techniques for natural turf sports surfaces (BS EN 12231:2003 & BS EN 14954:2005). During the running trials, compared to the other two surfaces, the sandy condition was hardest prior to and after participant testing. The shear data indicate that the rootzone condition had lower values than the clay and sandy conditions. Thus there appear to be distinct differences in the mechanical properties of the three turf surfaces.

Despite the differences in mechanical properties, kinematic results indiate similar running patterns on the three turf conditions. Based on the study hypotheses, a greater initial knee flexion and lower ankle dorsi-flexion would be expected on the harder sandy surface than on the clay or rootzone. However, similar values were observed for these kinematic variables across all three surfaces. The consistent production of ankle and knee joint kinematics with changes in mechanical surface properties could suggest that humans prefer to maintain similar geometries when running on a variety of natural turf surfaces.

Alternatively, the mechanical properties of the natural turf conditions may not have been sufficiently different to elicit changes in human response during running.

The lack of difference in running kinematics with changes in turf surface properties does not necessarily indicate that players will move similarly on different surface types for all movements. For example, turning or accelerating on the surfaces may require changes in movement patterns according to the hardness or shear properties of the surfaces. Turning and accelerating movement tasks that result in a change of direction of the performer have been found to yield approximately 4.2 times the magnitude of peak braking force and 3.8 times the magnitude of horizontal (braking) loading rate compared to when running on natural turf (Stiles et al., 2007). This finding therefore supports the notion that a turning manoeuvre if performed at subject self selected sub-maximal speeds result in the participant experiencing higher magnitudes of horizontal loading and rates of loading compared to running at 3.83 $m.s^{-1}$. Compared to running, turning imparts greater horizontal forces and rates of loading on the turf thus placing greater reliance on the shear strength properties of the surface in order for the participant to successfully and consistently perform the movement in a stable manner. Given the increased need for the particpant to utilise mechanical properties of the turf surface when performing a turning manoeuvre, it is suggested that this movement would provide more scope to study kinematic measures of human response with changes in natural turf condition. Future work will assess kinematic response to different turf surfaces when performing a turning movement.

5- Conclusions

A kinematic analysis of running on three mechanically distinct natural turf surfaces has revealed that participants maintain similar ankle and knee joint geometries across all surfaces. Future work will assess kinematic response when performing a turning manoeuvre with changes in natural turf condition.

6- Acknowledgements

The authors gratefully acknowledge the funding of this research by the Engineering and Physical Sciences Research Council, UK under project EP/C512243/1(P).

7- References

[B1] BS1377-9:1990. Soils for civil engineering puposes – Part 9: in-situ tests. Brtish Standards Institute, London. ISBN 0 580 18242 8.

[BY1] Bobbert, M.F., Yeadon, M.R. and Nigg, B.M. Mechanical analysis of the landing phase in heel-toe running. Journal of Biomechanics, 25(3): 223-234, 1992.

[C1] Clegg, B. An impact testing device for in situ base course evaluation. Australian Road Research Bureau Proceedings, 8: 1-6, 1976.

[CL1] Coyles, V.R., Lake, M.J., & Patritti, B.L. Comparative evaluation of soccer boot traction during cutting manoeuvres – methodological considerations for field testing. In S.J. Haake (Ed.), *The Engineering of Sport* (p. 183-190). Blackwell Science: Cambridge, 1998.

[DD1] De Wit, B., De Clercq, D. and Aerts, P. Biomechanical analysis of the stance phase during barefoot and shod running. Journal of Biomechanics, 33: 269-278, 2000.

[D1] Department of Health At least five a week – evidence on the impact of physical activity and its relationship to health. Department of Health, Physical Activity, Health Improvement and Prevention, 2004.

[DC1] Dixon, S.J., Collop, A.C. and Batt, M.E. Surface effects on ground reaction forces and lower extremity kinematics in running. Medicine and Science in Sports and Exercise, 32(11): 1919-1926, 2000.

[ES1] Eils, E., Streyl, M., Linnenbecker, S., Thorwesten, L., Volker, K., & Rosenbaum, D. Characteristic plantar pressure distribution patterns during soccer-specific movements. *The American Journal of Sports Medicine*, 32(1): 140-145, 2004.

[GM1] Gaskin, G. J., Miller, J. D. Measurement of soil water content using a simplified impedance measuring technique. Journal of Agricultural Engineering Research. 63: 153-160, 1996.

[HB1] Holmes, G., Bell, M. J. A pilot study of the playing quality of football pitches. Journal of the Sports Turf Research Institute. 63: 74-91, 1986.

[K1] Kolitzus, H.J. (1984). Functional standards for playing surfaces. In E.C. Frederick (Ed.), Sport shoes and playing surfaces: Biomechanical properties (p. 98-118). Human Kinetics Publishers Inc: Champaign, Illinois.

[NY1] Nigg, B.M. and Yeadon, M.R. Biomechanical aspects of playing surfaces. Journal of Sports Sciences, 5: 117-145, 1987.

[SB1] Soutas-Little, R.W., Beavis, G.C., Verstraete, M.C. and Markus, T.L. Analysis of foot motion during running using a joint co-ordinate system. Medicine and Science in Sports and Exercise, 19(3): 285-293. 1987.

[SL1] Spencer, M., Lawrence, S., Rechichi, S., Bishop, D., Dawson, B. and Goodman, C. Time motion analysis of elite field hockey, with special reference to repeated-sprint activity. Journal of Sports Sciences, 22, 843-850, 2004.

[SD1] Stiles, V.H., Dixon, S.J., Guisasola, I.N. and James, I.T. Biomechanical response to variations in natural turf surfaces during running and turning. In: 'STARSS 2007', Proceedings of the First International Conference of the SportSURF Network, September 2007, Eds P. Fleming, C. Young, S. Dixon, I. James, M. Carre, C.Walker, ISBN 978-1-897911-30-3, Loughborough University, UK, 2007.

[SD2] Stiles, V.H., Dixon, S.J., & James, I.T. An Initial Investigation of Human-Natural Turf Interaction in the Laboratory. In E.F Moritz & S. Haake (Eds.), The Engineering of Sport 6, Vol 3, (pp. 255 - 260). New York: Springer, 2006.

[U1] UEFA, Turf first in the Netherlands, (2005) Retrieved from www.uefa.com 06/10/05.

[VD1] Vaughan, C.L., Davis, B.L. and O'Connor, J.C. Dynamics of Human Gait. Human Kinetics: Champaign, IL, 1992.

[W1] WHO (2003). Health and Development Through Physical Activity and Sport. WHO/NMH/NPH/PAH/03.2, World Health Organization, Geneva, Switzerland.

[W2] Woltring, H.J. On optimal smoothing and derivative estimation from noisy displacement data in biomechanics. Human Movement Science, 4(3): 229-245, 1985.

Approval for publication Signed ______________ Date ________ Number of amended pages returned ________

REVIEW ARTICLE

Sports Med 2009; 39 (1): 1-20
0112-1642/09/0001-0001/$49.95/0

Natural Turf Surfaces

The Case for Continued Research

Victoria H. Stiles,[1] *Iain T. James,*[2] *Sharon J. Dixon*[1] and *Igor N. Guisasola*[2]

1 School of Sport and Health Sciences, University of Exeter, Exeter, UK
2 School of Applied Sciences, Cranfield University, Cranfield, UK

Contents

Abstract

It is well documented that health and social benefits can be attained through participation in sport and exercise. Participation, particularly in sports, benefits from appropriate surface provisions that are safe, affordable and high quality preferably across the recreational to elite continuum. Investment, construction and research into artificial sports surfaces have increased to meet this provision. However, not all sports (e.g. golf, rugby and cricket) are suited to training *and* match-play on artificial turf without compromising some playing characteristics of the games. Therefore, full sport surface provision cannot be met without the use of natural turf surfaces, which also have an important role as green spaces in the built environment. Furthermore, a significant number of people participate in outdoor sport on natural turf pitches, although this is a declining trend as the number of synthetic turf surfaces increases. Despite natural turf being a common playing surface for popular sports such as soccer, rugby and cricket, few biomechanical studies have been performed using natural turf conditions. It is proposed that if natural turf surfaces are to help meet the provision of sports surfaces, advancement in the construction and sustainability of natural turf surface design is required. The design of a natural turf surface should also be informed by knowledge of surface-related overuse injury risk factors.

This article reviews biomechanical, engineering, soil mechanics, turfgrass science, sports medicine and injury-related literature with a view to proposing a multidisciplinary approach to engineering a more sustainable natural turf sport surface. The present article concludes that an integrated approach incorporating an engineering and biomechanical analysis of the effects of variations in natural turf media on human movement and the effects of variations in human movement on natural turf is primarily required to address the longer-term development of sustainable natural turf playing surfaces. It also recommends that the use of 'natural turf' as a catch-all categorization in injury studies masks the spatial and temporal variation within and among such surfaces, which could be important.

The health benefits gained from participation in sport and exercise are well documented.[1,2] For example, in the UK, recognizing that 'sport matters', a detailed action plan was drawn up by the UK Department for Culture, Media and Sport[3] to modernize and integrate the aims of implementation groups (Sport in Education, Sport in the Community and Sporting Excellence), to promote and achieve physical activity for all.[3] However, the significant benefits for population health from increased, regular participation in sport require provision and access to community sports facilities in a number of different environments. In 2008, for the first time, global urban population will reach 50% and is predicted to reach 86% in 2050.[4] Consequently, facilities for sport will be subject to increased intensification as land-use pressure increases, reducing the area available for sports facilities.

It is recognized that participation in sporting activity can take place on almost any surface and within a limited space. However, at the elite/professional and recreational/community levels within the developed and to some extent the developing world, a reasonable quality, safe sports surface is desirable. The provision of quality surfaces is also likely to encourage participation.[5] The performance characteristics of a surface are sport specific and will vary with the level at which a sport is played. They should allow a participant to perform to the best of their ability, without an increased risk of surface-related injury. In addition, high-quality, high-performance sports surfaces have a direct impact on elite/professional athlete performance and the status and individual rewards this brings. Provision of such surfaces by the sports industry, sports governing bodies and national governments is a key requirement for realizing the benefit to individual sports and national morale and esteem from such successes.

The challenge in sports surface engineering is to meet the demand for such surfaces within the different client expectations and budgets (both construction and ongoing maintenance) of different sports facilities. Several studies have illustrated, however, the danger of engineering sports surfaces on the basis of surface performance and durability, without consideration of human interaction.[6-8]

The majority of studies in this area have been in relation to synthetic sports surfaces, with the assumption that natural turf surfaces are a benchmark standard for safety. However, development in the engineering of natural turf surfaces for more intensified use, and use within enclosed stadium environments, has resulted in significant changes in mechanical properties that should not be ignored. Furthermore, the availability of natural turf surfaces for a number of sports at elite level is necessary (e.g. golf and cricket) and the only option in many communities for the provision of sports facilities. In rugby union, new generation long-pile synthetic turf pitches can be used for international rugby if both teams agree, under Regulation 22 of the International Rugby

Board.[9] To date, this has not taken place and the current norm is for synthetic surfaces to be used for elements of training within elite-level rugby and for natural turf pitches to be used for both competition and training. The adoption in soccer is different, with a number of elite teams in Europe playing competitive soccer on certified long-pile synthetic turf and the surface has been used for international fixtures with approval from Fédération Internationale de Football Association (FIFA), the world governing body for football (soccer).[10] However, the majority of surfaces for both training and competition remain natural turf.

The engineering of sports surfaces and the understanding of surface-related injury requires an integrated understanding of both surface mechanical behaviour and player biomechanical behaviour. This integration is two-way: by improving knowledge of surface effects on players, the understanding of injury risk can be improved; likewise, through an improved **characterization ((Author: is this the correct word? Would 'analysis' be better?))** of human movement and loading on the surface, surface design and material selection is improved. This is critical in the development of natural turf surfaces that have properties that vary in space and time. This article considers the extent of our current understanding and highlights where significant contributions are required in the particular context of natural turf surfaces.

1. Sports Facility Provision: The Role of Natural Turf

Affordable, safe and appropriate sports facilities are an important contribution to obtaining a healthy nation through sport and exercise participation.[1-3] A survey of households in England performed by 'Sport England' considered two questions: (i) where do people participate in sport for all reasons (e.g. recreation, fitness, competition); and (ii) where do people participate in sport for competition only? **((Author: please confirm that rewording is ok))** Natural turf surfaces were important for only three (soccer, golf and tennis) of the top ten sports when ranked by participation in the 4 weeks prior to the survey (table I).[11] This list is dominated by individual, indoor/home-based sports. In terms of competitive sport, however, natural turf was important in five of the top ten sports in the same survey (table I).

1.1 Sports Participation

Synthetic turf sports surfaces have made an important contribution to increased opportunities for participation in organized competitive sports. Traditional sports such as hockey, soccer, rugby, tennis, golf and cricket require considerable investment (both financial and spatial) for surface provision. Traditionally, field hockey, soccer and tennis were played on natural turf before the development of artificial sports surfaces allowed year-round playing opportunity and in hockey, improved standards of play.[12] The continuing growth of artificial surfaces in school, community and club sport is important to provide a playing surface where performance is less influenced by adverse weather conditions, requires lower levels of maintenance[13-15] and provides the opportunity to make relatively smaller sports areas more cost effective due to a higher tolerance of regular multi-sport use. In comparison, a functional outdoor natural turf environment is heavily influenced by seasonal and day-to-day weather variations, intensive maintenance, drainage, its response to wear[14,16-18] and the provision of space to rotate pitch usage as a method of maintenance, restoration and damage prevention.

Comparative data for the costs of maintaining synthetic and natural turf are limited. However, a study by McLeod[19] indicated that costs were similar on an 'area of pitch' basis, but on a 'per hour of use' basis, the cost of maintaining natural turf was 3.6-fold greater than synthetic turf, including the cost of synthetic turf installation. Consequently, in some cases, traditional school playing fields have been downsized in order to raise capital for the rebuilding of sports facilities that utilize a synthetic pitch.[3] There is a danger, however, that this approach of selling portions of the school playing field in return for constructing a smaller (but full-sized for competitive sport) synthetic pitch reduces the area available for

Table I. The variation among surfaces used for different sports as indicated in a survey of English households as a percentage of respondents (adapted from Sport England[7])

Rank	Activity	Participation				Competition		
		indoor	home	outdoor	activity	indoor	home	outdoor
1	Swimming	45	10	45[a]	Rugby	0	0	100[b]
2	Keep-fit/yoga	45	40	15[c]	Bowls	53	0	47[b]
3	Snooker/pool/billiards	58	11	0	Hockey	0	0	100[d]
4	Cycling	0	3	68[c,e]	Cricket	0	0	100[b]
5	Weight training	45	47	0	Soccer	19	0	81[b,d]
6	Running (jogging)	0	0	82[c,e]	Netball	NR	NR	NR[f]
7	Soccer	19	0	81[b,d]	Golf	0	0	96[b]
8	Golf	0	0	96[b]	Motor sports	NR	NR	NR[e]
9	Ten-pin bowling	81	0	0	Athletics (T&F)	NR	NR	NR[b,g]
10	Tennis	0	0	100[b,f,h]	Volleyball	NR	NR	NR

a Water.

b Natural turf.

c Recreational open space.

d Synthetic turf.

e Road.

f Hard-court.

g Acrylic/polyurethane.

h Clay.

NR = not reported; T&F = track and field.

general play and unorganized sports activity in schools (National Playing Fields Association[20]), especially if the access to the new synthetic pitch is restricted during break and lunch times.

Within the UK, the maintenance of a natural turf sports environment has been highlighted as important for the protection of green spaces and playing fields for recreational sport in the community.[3] This is a priority for the UK and reflects the high urban population density and competition for land in that country and the urban ecosystems services that natural turf sports surfaces can provide. In other countries, priorities can be expected to differ depending on resources (both capital and land) and environmental and participation strategies.

1.2 Replication of Natural Turf: Playing Characteristics and Injury Patterns

The nature and properties of natural turf are also fundamental to the playing characteristics of soccer, rugby, golf and cricket. In cricket for example, pitch properties influence the range of shots played, ball speed after impact with the surface, the amount of seam movement and ball spin characteristics.[21] While these properties could be achieved with synthetic surfaces, controlled temporal variations in such properties are desirable and essential for the game; cricket is a sport that can end in a draw after 4–5 days of play; the likelihood of a positive result (win/loss) is increased when the deterioration of the pitch balances the game in favour of the bowler. Of course if this happens too soon, a 5-day game can finish prematurely, resulting in lost revenue from crowds and media coverage. In soccer, such temporal variation and spatial variation is undesirable and, as a consequence, there is an increasing use of sand materials to construct surfaces, with a resultant increase in maintenance costs for water, nutrients, etc. Another important characteristic is the natural temperature regulation and lubrication of the surface from transpiration in the grass plant. Grass plants can transpire at 110 kg [H_2O]/m^2/hour,[22] with a latent heat of vaporization of 2.43 MJ/kg at 30°C.

Modification of hockey pitches that started in the 1970s from natural turf to artificial turf surfaces resulted in certain playing skill adaptations with a loss of some surface-related skills and an enhancement of other skills together with a faster-paced game.[12] The playing characteristics of hockey therefore changed as a result of the move from a natural turf pitch to artificial surfaces.

The development of modern synthetic turf has focused on reproducing the playing characteristics of natural turf. This development strategy has been motivated by experiences from the introduction of the first generation of synthetic turf into soccer in the early to mid 1980s. The early surfaces were characterized by higher stiffness, higher sliding friction and greater heat retention than natural surfaces. Consequently, players experienced higher ball bounce, faster ball roll, and significant skin damage and lower limb discomfort. 'First generation' describes the early nylon surfaces of the 1970s characterized by skin abrasions and excessive traction. 'Second generation' sand-filled surfaces with a typical pile length of 22–25 mm, are commonly used in recreational field hockey and multi-sport community facilities, but were deemed unsuitable for soccer when trialed in the 1980s. FIFA now permit and actively promote the use of a new generation of synthetic turf surfaces that meet new playing standards, commonly termed 'third generation' surfaces.[10] These surfaces have increased shock absorbency, longer pile length (typically 40–60 mm) and a rubber granular infill. However, variations in injury patterns derived from play on natural turf and a specific third-generation synthetic turf product (FieldTurf **((Author: does this product require a trademark or registered mark?))**-polyethylene/polypropylene fibre blend with silica sand and ground rubber infill) suggest that while the artificial turf has been designed to closely replicate natural turf characteristics, injury outcomes and therefore characteristics of play between the surfaces may not be comparable.[23]

A 5-year study of 240 Texas (USA) high-school American Football games found that the artificial and natural turf surfaces yielded unique patterns of injury incidence. While a greater incidence of muscle-tendon overload injuries, abrasions, non-contact, running and sprinting injuries (significant at $p<0.05$) occurred on the artificial surface, lower incidences (non-significant) of concussion and ligament tears were reported on the third-generation artificial turf compared with natural grass.[23]

The observation that the majority of natural grass surfaces studied were an over-seeded Bermuda grass blend, existing with <46 cm (18 inches) **((Author: conversion to metric ok?))** of **((Author: annual?))** rainfall, <40% humidity in declining temperatures and in an overused multi-purpose environment highlights the challenges in providing natural turf surfaces in environments with a large range in temperature and where water resources are limited. The key point is that natural turf surfaces are geographically and temporally variable in both training and competitive use and so comparisons between synthetic and natural turf will be difficult to control.

The monitoring of injury incidence on natural turf and third-generation artificial surfaces during soccer match play has revealed a differing pattern to that occurring during training. A comparison of injury incidence sustained by men and women over a two-season period during soccer matches on natural turf and third-generation artificial surfaces in North America was performed by Fuller and colleagues.[24] While no major differences were observed between surfaces, it was observed that the most common season-ending injuries for men on artificial turf and grass were a hamstring tear and anterior cruciate ligament (ACL) tear, respectively. For women, a tear of the ACL was the most common season-ending injury on both surfaces. The incidence of ankle sprains in men remained similar on both surfaces, whereas for women there was a significant reduction on artificial turf compared with grass. The study concluded that the overall incidence of injury when playing matches on third-generation artificial turf was similar to that experienced on a natural turf surface.[24]

The comparison of injury incidence during soccer training by Fuller and colleagues[25] over the same 2-year period revealed that for men, mild (4–7 days of training missed) and moderate (8–28 days of training missed) injuries were significantly higher ($p < 0.05$) on artificial turf than on natural turf. For women, however, the incidence of mild injuries was significantly lower on artificial turf than on grass.[25] The most common season-ending injury for men during training was ankle ligament tear, which was significantly more common on artificial turf compared with natural turf. Foot injuries for men were also significantly higher ($p < 0.05$) on artificial turf than on natural turf. On natural turf, the most common injury sustained by men was knee ligament tear. Knee ligament tear was the most common season-ending injury for women on both artificial and natural turf.[25] Thus, whilst similar injury patterns appear to exist on natural turf and third-generation turf during soccer match play, injuries sustained during training differ for the two surface types. In both these studies, the specifications of different synthetic and natural turf surfaces were not specified.

A UEFA **((Author: Union of European Football Associations?))** funded study by Ekstrand et al.[26] compared reported injury incidence for 290 soccer players at ten elite European clubs with third-generation synthetic turf pitches with 202 players from the Swedish Premier League playing home fixtures on natural turf. The authors concluded that the overall risk of injury on artificial turf was no higher than on grass. However, the study observed significantly higher incidences of ankle sprain during matches on synthetic turf and significantly lower incidences of lower extremity strain compared with natural turf. A reduced tendency towards severe training injuries on natural turf has been suggested to warrant further investigation by the authors.[26] This observation of different patterns for training injuries compared with match injuries is consistent with that of Fuller and colleagues.[24,25] Ekstrand et al.[26] also suggested that further research with larger sample sizes was required to confirm these findings. It was noted that not all third-generation surfaces included in the study met subsequent FIFA quality standards.

A study specifically assessing the injury risk of young (under 17 years) female soccer players (109 league teams; 2020 players) in Norway whilst training and playing on artificial turf (combination of second- and third-generation pitches) and natural turf reported that injury incidences, calculated as the number of injuries per thousand hours of training, and match-play exposure were similar for artificial and natural turf.[27] However, limitations of the study included a lack of control over the specification of both the synthetic and natural turf studied, the maintenance status of all surfaces and limited monitoring of weather conditions.

A comparison between artificial (undisclosed type) and natural turf properties for soccer by Martinez et al.[28] took into account anecdotal opinions from two sets of user groups followed by mechanical assessment of surface properties. User groups were found to prefer natural turf perceiving that impact reduction was higher (supported by mechanical impact test results), ball roll was slower, the surface was more comfortable (reduced heat retention and improved moisture retention) and leg and muscle problems were less frequent compared with artificial turf. Preference for soccer play on natural turf compared with artificial turf was also found by Dick et al.[29] Martinez and colleagues[28] suggested that in order for natural turf characteristics to be reproduced in artificial form, the following criteria needed to be achieved: increased force reduction (based on an artificial athlete test using a flat foot with studs) yielded from first, second and third consecutive impacts of 10% compared with force reduction magnitudes for each impact on existing synthetic surfaces; increased vertical deformation at impact by 5 mm and by 3 mm during second and third impacts **((Author: respectively?))** (artificial athlete) and reduced ball bounce by 10% in both dry and damp climates.[28]

The comparison studies available highlight that the playing characteristics and injury patterns on artificial turf are compared against the benchmark characteristics of natural turf. However, several authors have cited a lack of control over and reporting of natural turf maintenance status, temperature, humidity, soil moisture content and frequency of use.[23,27] The benchmark for these studies has thus been a variable one. The continued use of natural turf surfaces in both training and competition for a variety of sports requires not only guidance on optimum maintenance techniques, but primarily an understanding of what characteristics of a natural turf surface are desirable and how these can be engineered consistently and in a sustainable manner.

The new third-generation turf has gone a considerable way to providing an improved artificial playing surface for some sports traditionally played on natural turf and the numbers of these surfaces will increase globally. However, the unsatisfactory replication of some playing characteristics of artificial turf highlights the importance of maintaining the availability of natural turf playing surfaces. Evidence of variations in injury patterns (whilst not necessarily of a negative nature) when playing on artificial turf compared with natural turf highlights the need for continued and further research into the causal mechanisms that explain the injury on both types of surface, rather than just comparative studies.

1.3 Financial Considerations

The initial capital costs of constructing and maintaining an artificial turf pitch are considerable and where capital resources (and ongoing funds for maintenance) are not available, the importance of and reliance on natural soil and turf surfaces to provide a suitable area for recreational and club sports use within these communities is increased. Just as with synthetic turf, the modern natural turf pitch has been developed significantly in the last 20 years at both the elite and, to a lesser extent, the recreational level of the game. The principal aim in the development of natural turf surfaces has been to improve infiltration and drainage of the surface. Modern surfaces are constructed from high sand content rootzone materials, which are free draining with lower water retention[16] and reduced sensitivity of shear strength to increased moisture content. This increase in the sand content of construction materials is the largest difference between the 1970s and modern surfaces.[30] However, the consequences of using more freely draining, higher sand content materials are significant. In terms of environmental sustainability, there is an increased use of scarce water resources for irrigation and increased use of fertilizer due to lower nutrient retention. In the elite stadium context, such resources are available and necessary to produce the aesthetic qualities required for television in particular and even include the use of enhanced-growth light systems. It is for this reason, however, that such surface construction materials are not suitable for recreational facilities, where such resources are not available. Alternative approaches to providing sustainable turf pitches are therefore required, but not necessarily in an artificial form, depending upon the sport, resources and whether an ecosystem service is considered important.

Recreational surfaces in the UK have developed significantly following investment from lottery funding and professional sport (through organizations such as Sport England and the Football Foundation). For example, since 1995, Sport England has invested ψ38.3 million in natural turf-related projects and ψ64.6 million in synthetic turf pitches and multi-use games areas. Since 2000, the Football Foundation has funded 199 natural turf development projects and 163 synthetic turf projects. This is based on an aim to increase access to facilities and increase intensification of use of facilities. The demand for quality surfaces has risen with population increase, increased pressure on land in urban spaces and increased expectations of surface quality from participants through the television images of surfaces. The challenge for providers such as local authorities is to provide quality facilities that can sustain intensified use without increased risk of injury within budgets that are often limited or have competition for resources.

1.4 New Natural Surfaces

The demand for hard-wearing surfaces that do not increase injury risk **((Author: rewording OK to clarify start of new paragraph/section?))** has resulted in a significant change in mechanical properties, in particular increased stiffness (important in ball- and player-surface interactions) and shear strength (important in player-surface traction). This is reflected in the fact that whilst minimum values for traction are reported in the performance quality standards for natural turf of both the English FA **((Author: Football Association?))** and the Institute of Groundsmanship, maximum values are not reported. This is an historical anomaly; the concept of injury from high traction was not considered in the past because creating surfaces with sufficient traction for player stability was the principal challenge facing grounds staff.

Thus, over the past 20 years, there has been a significant change not only in the nature of synthetic turf surfaces, but also in the development of natural turf surfaces. New natural turf surfaces meet the requirements of the players for faster, higher traction surfaces, reflecting the increased fitness, strength and speed and more advanced technique developed over the same time period. With increased surface stiffness, player energy cost is reduced[31] and speed differentials between players are increased. Furthermore, increased uniformity of surface quality allows improved technique development, as ball/equipment behaviour becomes more predictable. In parallel with this, the fitness, speed of movement[32] and turning, and equipment of players have changed **((Author: rewording OK?))**. To ignore these developments without assessing the increased risk of injury is foolhardy. The highest value players are playing on **such ((Author: stiffer?))** surfaces, and the majority of recreational players are playing on different surfaces with the same or different equipment. To study the change in injury risk requires an integrated investigation in order to understand the changing nature and properties of natural turf surfaces as player performance, movement and equipment also develop.

Advancement in natural turf pitch construction and engineering continues to be required to provide sustainable sports pitches for competitive and training purposes in sports such as rugby, cricket and golf where the characteristics of these games are generally not suitable for current artificial turf surfaces to be used. The initial capital costs of constructing and maintaining an artificial turf pitch are also too much for many providers. Thus, the importance and reliance on natural turf to provide a suitable area for recreational and club sports use within these communities is increased.

2. Relationships between Sports Surfaces, Biomechanics and Injury

A relatively large amount of research has been published on the mechanical properties of artificial sports surfaces and human interaction with these surfaces,[14,33-37] compared with research documenting assessment of natural turf.[38-41] In general, the available research does not point towards a preferential use of either natural or artificial surfaces with regard to their respective associations with injury prevalence.[23-29] Interpretation of findings is complicated by the varied properties of both natural and synthetic playing surfaces utilized in different studies. For example, early work studying synthetic surfaces was based on first-generation surfaces, which, as previously noted, have distinctly different properties to recent third-generation pitches. Results from earlier studies are still relevant to this review as many synthetic pitches currently used for multi-sports use are similar to second-generation synthetic turf sports pitches, certainly in the UK. For school and community artificial pitches it is also not always appropriate to install a third-generation surface because whilst suitable for soccer play, it is not possible to play tennis or field hockey, and consequently multi-sport use is restricted. Artificial turf pitches resembling the older second-generation turf designs are thus still in production, although with improved shock absorbent layers and a new generation of short piled, sand-dressed surfaces for field hockey.

Increased levels of impact,[42-47] altered joint movement patterns,[48,49] an increase in eccentric muscle activity[50] and differences in resistance to sliding[46,51] are mechanisms that have been suggested to facilitate an observed increase in injury rates with the increased use of older generation artificial turf surfaces in sport.[46,52-54] However, a direct cause-effect relationship has not been established between increased artificial turf use and a particular type of injury.

2.1 Comparison of Surfaces

Evidence of natural turf injury analysis in the literature is relatively sparse. One of the first studies to consider the impact of artificial turf on injury[7] reported that studies have shown natural turf to yield a lower number of injuries compared with artificial turf, citing that deformation of the surface was the most variable and perhaps beneficial factor for natural turf over artificial turf. While perhaps not yielding as many injuries as artificial surfaces, injuries still occur on natural turf. A prospective study on the aetiology of soccer injuries reported that 24% of injuries were correlated with playing surfaces (Ekstrand, 1982 ((**Author: please supply full details for this original reference so that it can be added to the reference list**)) in Nigg and Yeadon[14]). It was assumed that features of a natural turf surface such as uneven playing ground, hardness and inappropriate friction characteristics were connected with injury prevalence (Ekstrand, 1982) ((**Author: please supply full details for this original reference so that it can be added to the reference list**)). A comparison between injury rates based on tennis surface type using elite male players revealed that competing on grass yielded a higher frequency of player medical treatments compared with hardcourt or clay.[55] Tactical and surface-enforced differences were suggested by the author to elevate injury risk when playing on grass (reduced sliding, lower ball bounce, variations in ball speed) compared with clay.

2.2 Traction

Hardness and traction on natural turf have been cited as the two main surface characteristics that may be related to injury incidence.[56] Accidental or acute injuries as a result of inappropriate magnitudes of traction on natural turf sports surfaces have received some attention in the literature. Efforts to reduce the amount of surface wear during sports use through soil material reinforcements, in the form of polyester nylon meshes near the soil surface, have been linked with an increased risk of ankle and knee joint injuries if feet become locked in the mesh.[57] The type of grass used to construct pitches also influences traction.[56,58] Traction on the soccer pitch is a function of soil type, soil density, grass root density, soil moisture content and shoe-surface interaction (influenced by the choice of stud pattern). For example, Bermuda (*Cynodon dactylon*) grass is suggested to result in greater shoe-surface traction compared with perennial ryegrass (*Lolium perenne*).[58] By the nature of its growth, Bermuda grass contains horizontally creeping stolons, which form a surface mesh that increases resistance to wear and also traction compared with perennial ryegrass, which is non-stoloniferous.[58]

Although shoe-surface traction is frequently cited in the literature as an important consideration in the cause and prevention of injury,[6,59-61] optimal recommendations of shoe-surface frictional characteristics have been difficult to determine.[46,51] According to Stucke et al.[51] variations in the amount of friction required depends on what type of movement is occurring between two contacting bodies (dynamic friction). Sports movements often require a static component of friction whereby movement suddenly ceases or begins from a position of rest. In these cases of static friction, the relative movement between two contacting surfaces is zero and this allows large horizontal ground reaction forces to be generated in either a stopping (decelerating) or accelerating movement. Typical vertical (Fz) and horizontal (Fy) ground reaction force data are presented in figure 1 from a participant accelerating from rest, on a natural turf surface while wearing studded footwear (soccer boots). The force-time history demonstrates the requirement of relatively large horizontal forces (approximately 0.6 bodyweights) in order to propel the body forward from a static standing position

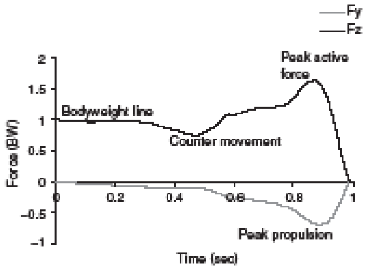


Fig. 1. Typical vertical (Fz) and horizontal (Fy) ground reaction force time histories for a subject accelerating from rest on a natural turf surface wearing studded footwear. BW = bodyweight. **((Author: correct definition?))**

where the relative movement between the soccer boot and the turf surface was zero.

When the properties of the contacting surfaces are not sufficient to provide coefficients of friction that meet the requirements of the movement (insufficient force-locking connection), spikes in the case of cricket and athletic track footwear or studs (cleats) in the case of rugby, soccer and field hockey provide a 'form-locking connection' between the shoe and surface.[51] These studs aim to improve traction between the boot and surface and also guard against too much traction-cited **((Author: what do you mean by 'traction-cited' in this context?))**, for example as a potential cause of non-contact ACL injury of the knee and twisting injuries of the knee and ankle.[62] The configuration and length of these studs have received attention.[59,62,63] However, a definitive conclusion regarding appropriate stud length and configuration to minimize injury occurrence has not been reached. Study in this area is hindered by the ethical considerations of knowingly administering the use of a high traction boot to players during a season in order to test their response, which may be considered reckless.[56] Orchard[56] suggests that modification of the playing surface holds the key to providing players with a universal method of reducing shoe-surface traction and thus reducing the relative risk of injuries related to shoe-surface locking. Whether this is realistic is questionable due to the increased scale of engineering and variability when constructing surfaces in different environments – integrated surface-footwear studies remain critical for reducing injury risk, particularly given the commercial nature of footwear design.

2.3 Seasonal Variation

Climate and weather conditions can have a large influence on the playing conditions of natural turf. According to Australian Football League surveillance, a trend has been demonstrated for higher incidence of ACL injuries on harder natural turf ground compared with softer ground in Australian Rules football.[58,64,65] In a review of the influence of climatic conditions on the ground and the occurrence of lower-limb non-contact injuries in football (including all codes of football: soccer, rugby union, American football, Australian football league), Orchard[56] reported that the majority of studies found an early season bias towards a higher incidence of injury when games were played on natural turf over a typical autumn-winter season (harder ground in the autumn season). In contrast, where football (including all forms) was not played over an autumn-winter season or in subtropical climates, an early season bias was found to be non-existent. The variation in ground conditions (traction and hardness differences in autumn) during a typical autumn-winter season was suggested to be partially responsible for the early season injury bias across all codes of football.[56]

A comparison of injuries incurred during **2-old** **((Author: what do you mean by 2-old?))** winter seasons (typically August to April) of English rugby league, a new condensed winter league (August 2005 to January 2006) and the subsequent new summer season of rugby (March to August, 1996) has been performed.[66] This assessment of seasonal variation on injury incidence revealed an increased incidence of injuries per 1000 hours of match play over the four playing seasons studied. Specifically, the new summer season, which involved the least number of games played compared with previous seasons, incurred the highest number of injuries albeit ones that were less severe and required less surgical intervention compared with previous seasons. The researchers suggested that the significant increase in injury rates during the summer season compared with the previous condensed and continuous autumn-winter seasons were due to warmer weather where pitch drying conditions (evapotranspiration > precipitation) prevail, with resultant harder ground conditions.[16,66] Unfortunately, measurement of surface parameters was not reported in this study. A greater integration of injury monitoring, mechanical characterization and biomechanical studies should improve our understanding of injury and weather and climate effects on natural turf pitches.

Approaches to managing the changes in natural turf as a result of climate and weather conditions have been suggested. Orchard[56] reported that shoe-surface traction on natural turf pitches was likely to be higher when the ground is hard, dry and the grass cover and root density are at their greatest. In the early part of an autumn-winter football season, pitch conditions are likely to be harder and drier. Orchard[56] concluded that measures taken to reduce shoe-surface traction should be employed including adequate watering and softening of the ground in the early part of the season, consideration of moving the season of play to use more of the winter months, increased use of natural turf (perennial ryegrass, *Lolium perenne* L.) as opposed to playing on artificial turf and the adoption of boots with shorter studs when playing on hard ground. Aeration and loosening of the soil (the process of reducing soil bulk density and increasing air-filled porosity by the action of inserting solid tines or rotary blades) are also proposed. This is resource dependent as materials, equipment and finances are required to manage surfaces in this way (**(Author: please confirm that rewording is ok)**). For example, as competition for water increases, the ability to provide management of surfaces in this way could be limited, particularly at sub-elite levels of sport.

3. Quantifying Player-Surface Interaction

The player-surface interaction is a complex function of surface mechanical factors, human perception and human biomechanical response (both voluntary and involuntary). The interaction is two-way, the surface appearance and mechanical behaviour modifies the human biomechanical response, which in turn loads the surface, resulting in deformation that can change the surface behaviour and appearance. This interaction is variable in time (due to factors of player stamina, variable environmental conditions, cumulative use effects), in space (due to differential usage as part of the nature of the sport played), with the level of sport played and the age/size of the participants. To evaluate surface-related injury risk, it is necessary to quantify this interaction in terms of both surface mechanical and biomechanical parameters. Historically, the techniques to evaluate such parameters have been developed independently, but an integrated approach is proposed as necessary for understanding injury risk, surface performance and player performance simultaneously.

3.1 Surface Mechanical Testing

The development of methodologies for the testing of surface mechanical properties has been driven by: the need to benchmark synthetic turf surface performance against natural turf in the improvement of synthetic surfaces; and, the development of performance quality standards for the specification and improvement of natural turf surfaces.

Mechanical testing methodologies for natural turf can be divided into three principal groups: (i) ball-surface interaction; (ii) surface performance and aesthetics; and (iii) player-surface interaction. Ball-surface interaction tests comprise vertical and angled ball bounce behaviour from standard heights and initial velocities, and horizontal ball roll characteristics (speed, deceleration and deviation from straight line behaviour). These are important for the quality of the playing experience and are considered a priority for many players.[67] Aesthetics and surface durability will vary according to the nature of the sport played and the maintenance resources for the surfaces – again this is critical for the player and spectator experience. The majority of player-surface interaction tests are for friction/traction or hardness parameters designed to simulate loads applied by the human during sports movements. Traction is measured either by rotation or linear test devices. Linear sliding devices such as the sliding traction test measure the distance a weighted studded boot travels on a trolley when supported[68,69] or the force required to move a studded sled in a single direction. Such linear tests are thought to be analogous to the type of traction required when moving and stopping in a straight line, but a single test assumes the surface is isotropic and tests should be performed in different orientations with respect to the surface being tested. Rotational tests typically comprise a studded plate, weighted to represent a static human that is rotated using a torque wrench that traditionally measured peak rotational force,[33,70] but have been adapted to log torque continuously as the device is rotated.[61] The continuous measurement of torque has allowed the rate at which torque is developed to be quantified – termed rotational stiffness – revealing differences between surfaces that were not evident when comparing peak torque alone.[61] A number of devices, such as the Pennfoot apparatus[71] and Strathclyde Sports Turf Testing Rig[72] incorporate the recording of both linear and rotational tests in one device.

The described mechanical tests are simplifications of the player-surface interaction. In 'real' player-surface interactions, the orientation of the principal stress axes is rotated during the movement, the loading-rates are variable and the magnitude of the stresses is variable. In most surface characterization tests, the surface is stressed in only the surface-normal and parallel directions using either constant velocities or dynamic loads applied from constant heights to maintain constant energy. Biomechanical subject-based research can characterize the stresses applied to a surface in both space and time and from this an understanding of injury development and risk for different player-surface interactions **((Author: can be?))** established. Subject testing of surfaces is difficult, however, as the stress paths are variable from subject to subject and within subjects over time, and therefore do not provide a suitable basis for surface characterization or for governing-body-led accreditation schemes such as those of international governing bodies for football (soccer) [FIFA[10]], field hockey (Federation Internationale de Hockey[73]) and lawn tennis (International Tennis Federation[74]).

Determination of the hardness and stiffness of surfaces is important for the understanding of impact-related injuries, whether to the leg or the head. Test devices include 'Artificial Athletes' such as the Berlin and Stuttgart Artificial Athletes; cylindrical missile drop-test devices of varying complexity such as the ASTM F1702 device; and dynamic plate tests, which include the lightweight deflectometer. In reviewing all these devices, Young and Fleming[75] identified that all have limitations in their replication of actual player loading. However, a key requirement was for future devices to be designed to incorporate a range of loads, contact areas and load durations to be able to measure the surface response to typical stress paths applied to surfaces of a particular type, particularly where surface materials are known to be non-linear. There are continued efforts to develop test devices that are more complex and realistic in order to test surfaces, for example the force-controlled traction device of Carré et al.[63]

There is a potential difference in the requirements of sport injury and sports surface engineering research and the requirements of sports governing bodies, manufacturers, etc. to characterize surfaces for player safety and quality of play (often termed 'playability') in the field. Complex test devices are small in number and prohibitively expensive for wide-scale testing of surfaces at current prices. Therefore, simplified test devices and methodologies are required; a key question is to what extent the simplifications are valid. The challenge for engineering is to develop test devices that balance the requirements for accurate, representative data to ensure data quality and validity, with affordability and portability to encourage extensive and frequent data collection.

3.2 Surface Biomechanical Testing

There is a scarcity of biomechanical research in the field or laboratory that has involved natural turf. The nature of analysis tools used in biomechanics are not always appropriate for sports-specific analysis in the field.[76] Integrating natural soil media and sustaining turf growth in the laboratory environment complicates research into human interaction with natural surfaces, making natural turf-specific equipment difficult to assess and resulting in the assessment of equipment in an inappropriate environment. For example, previous assessment of studded soccer boots has taken place in the laboratory using artificial turf rather than natural turf.[40] Ideally, shoes should be assessed on the surface for which they are intended and vice versa.[77]

Biomechanical quantification of surface cushioning has included the use of force platforms, pressure insoles and accelerometers. Whilst there have been some attempts to site force platforms below natural turf in the field,[78,79] these have been focused on the provision of an appropriate environment for footwear testing, rather than the specific testing of natural turf surfaces. The recent application of pressure insoles placed within footwear to measure loads at the foot plantar surface has provided a more practical methodology for measurement of cushioning than the siting of a force platform within the turf surface. Patterns of plantar pressure distribution during soccer-specific movements have been assessed in the field on natural turf and red cinder surfaces.[41] The researchers highlighted a lack of soccer running pressure data in the literature and thus could only compare their soccer-specific data to running activity pressure data. A study comparing forefoot plantar pressure wearing three different soccer studded boot models while running on a treadmill and natural turf has highlighted the importance of testing footwear on appropriate playing surfaces.[39] This research found that treadmill running did not reflect the forefoot loading patterns derived when running on natural turf, as cleats were not able to penetrate into the surface. The researchers therefore suggested that analysis of cleated footwear should be undertaken on surface conditions for which the boots are intended. Peak pressures under metatarsals one, two and five were found to be related to foot landing characteristics and surface properties rather than the location of cleats below these aspects of the foot, thus potentially **informing ((Author: indicating a need for?))** footwear design for different surfaces.[39]

Tillman et al.[80] used pressure insoles to compare resultant ground reaction force for asphalt, concrete, a running track and natural turf. These authors detected no difference in loading between the tested surfaces, concluding that surface stiffness was not directly linked to injury risk through loading. This study provided a useful demonstration of the potential of pressure insoles to allow comparison of surfaces in the field, but did not utilize the full potential of pressure insoles – to provide detail on the distribution of force over the foot plantar surface. More recently, Ford et al.[81] compared a synthetic turf surface with natural grass using in-shoe pressure distribution. These authors reported peak pressure and relative load at nine plantar regions of the foot during cutting movements. They observed differences in loading for the two surface conditions, with greater peak pressures at the central forefoot and lesser **((Author: at the?))** toes for the synthetic turf and greater relative load at the medial forefoot and lateral midfoot for the grass surface. This comprehensive assessment of pressure distribution highlights the potential of pressure data to detect different surface cushioning. To improve our understanding of natural turf, different turf surface type and conditions require testing. Work has commenced in this area with comparison of pressure distribution for different soil densities.[82] Further studies using this technology should contribute to our increased understanding of natural turf surfaces.

The measurement of horizontal forces has taken place on natural turf surfaces to indicate traction behaviour. An analysis of horizontal forces in soccer boot studs while performing sports-specific movements (accelerating from rest, inner and outer zigzag and turning movements) has been performed.[83] While not detailing what surface these movements were performed on, the researcher suggested that a diverse pattern of stud configuration was required based on the utilization (maximum loads and direction of force applied to studs) during the range of movements. However, an assessment of shoe-surface traction using artificial and natural soccer surfaces and cleated boots concluded that aggressively cleated boots were not recommended due to their high resistance to rotation during cutting manoeuvres and subsequent risk of injury particularly of the ACL.[84]

There are few examples of analysis of movement patterns (kinematics) on natural surfaces. A study of cutting manoeuvres on artificial and natural turf has taken place in the field using movement speed as a measure of grip performance between shoe and surface and video analysis to provide information on boot-surface slip pattern.[38] An analysis of body and limb accelerations for a variety of surfaces in the field, including indoor and outdoor artificial turf and outdoor natural turf, has been performed to assess whether the characteristics of soccer-specific movement techniques are adapted for different surface conditions.[85] Maximum shank and pelvis acceleration were found to be similar between natural and artificial turf. The authors concluded that the findings were useful indicators of a comparable injury risk (assuming accelerations are correlated with injury prevalence) across all surface conditions.[85] Some initial kinematic findings have also been presented from participants running on a variety of natural turf surfaces in the biomechanics laboratory.[86] Initial and peak ankle and knee flexion angles during running appear to be maintained at similar levels even with distinct mechanical changes in turf type. Analysis of movement kinematics in addition to running, however, remains to be performed.[86]

3.3 Integrated Studies

The mechanical devices described above (**(Author: in which specific section?)**) fail to incorporate the complexities of human movement and therefore do not consider the influence of a variety of human movements on the behaviour of shoe-surface materials and frictional coefficients during a repertoire of available movements in sport.[51] Biomechanical human assessment of surface frictional properties using stopping, starting and turning movements has been performed;[51] however, the inclusion of natural turf undergoing a repeated range of tests remains a rarity.

Some work has been performed that used biomechanically validated magnitudes of vertical, shear and torque loads[87] within a portable mechanical testing rig to characterize properties of a sports surface including linear and rotational traction, vertical impact and a combined vertical, shear and torque impact test.[72] This research found that traction coefficients and peak torque were lower on a 3G surface (third-generation artificial turf) than on a natural grass pitch.

As stated above (**(Author: in which specific section?)**), the player surface interaction is two-way and studies that provide detail of the mechanism by which variations in human movement affect natural turf characteristics and performance are lacking. While the sports performance aspects of a surface can be assessed (ball bounce, ball roll, ball speed etc.) in relation to the composition and temporal characteristics of soil media, relatively little assessment of how the natural turf surface parameters affect the athlete have been performed, let alone the affect that variations in athlete movement can have on the surface. An integrated study investigated the effect of changing a soil surface from a soft to a hard condition by simultaneously measuring pressure distribution within the soil and the shoe when running.[82] An increase in the dry bulk density from 1460 to 1590 kg m^{-3} resulted in an increase in peak G of 125 to 235 g measured using a 0.5 kg Clegg Hammer. Peak heel force was significantly lower for the lower density soil condition, but vertical stress distribution within the surface only varied significantly with depth (100 vs 200 mm depth), not between soil densities as predicted by a linear elastic model of soil behaviour. Similarly, Stiles et al.[88] and Stiles et al.[89] reported pilot data on the inclusion of turf surfaces of contrasting soil types (and therefore mechanical properties) into the traditional biomechanics laboratory environment and showed

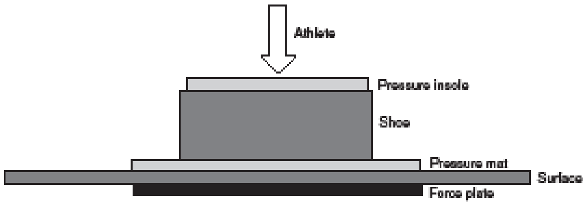


Fig. 2. A model to depict layers of the player-shoe-surface system between which loads should ideally be quantified.

significant differences in rates of loading between different surface materials in both running and turning movements. In the study of Stiles et al.,[89] the turf conditions were carefully controlled and monitored. Such integrated studies and the use of novel laboratory environments allow the stresses on the human and the surface to be analysed simultaneously. Ideally the loads experienced at each level of the performer/shoe/surface system (figure 2) should be quantified. Thus, better informed assessments of new or existing surfaces can then be made with regard to their effect on the player and surface performance (figure 3).

4. The Case for Further Research

Participation in sport and exercise activities yields important health and social benefits for the individual and reduced dependence on community primary care health provisions.[2] Promotion and attainment of a healthy nation can be aided by appropriate sports facilities that are affordable and safe. Benefits to health and society can be gained via participation in traditional, competitive sports such as hockey, football, tennis, rugby, cricket and lacrosse at school, club and elite level. Sports such as tennis, hockey and to some extent soccer have benefited from incorporating artificial surfaces into the game as they provide year-round playing opportunity. The influence of adverse weather conditions on the performance of a surface is also less when playing on artificial surfaces compared with natural turf. An artificial turf surface also requires a lower level of maintenance, can be constructed within a relatively small space and can tolerate regular multi-sport use compared with a natural turf surface.[13-15]

Artificial sports surfaces have made an important contribution to the provision of functional sports surfaces and increased sport participation. Currently, however, artificial turf surfaces do not adequately replicate the playing properties of all natural turf surfaces and thus are not suitable for every sport. There is therefore a need to continue to develop natural turf surfaces, the reasons for which are (i) the protection of green spaces and playing fields in the built environment is critical for urban ecosystem functioning; and (ii) the preservation of fundamental playing characteristics for sports such as soccer, rugby, golf, cricket and lacrosse, which are not well suited to play on any generation of artificial pitch, is paramount. There have been significant changes in natural turf properties over recent years in keeping with player requirements for a faster surface and higher traction component. The number of synthetic turf surfaces is increasing; however, a significant number of participants continue to play on natural turf at all ages and levels of sport. The sustainability of natural turf surfaces and the risk for injury they pose to players needs to be understood. Thus, further research is required.

Figure 4 illustrates a conceptual framework for further research. Soil physical properties vary in space and time;[90] the variability in natural sports surfaces needs to be understood and with the development of new construction techniques for natural turf surfaces using more frictional and reinforced soil media, the assumption that natural surfaces are a lower risk for participant

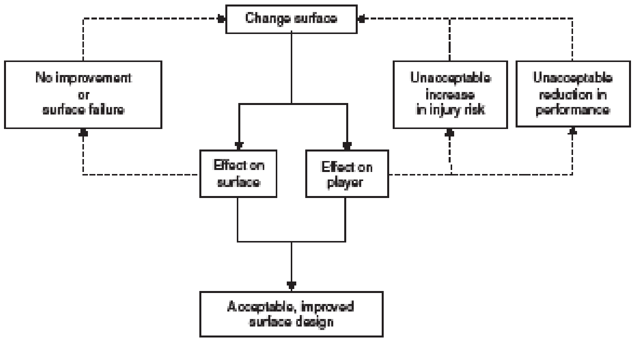


Fig. 3. A model for integrated development of surfaces. Any change in surface properties should be evaluated in terms of both the effect on the surface and the effect on the player (in terms of injury and performance). The model responds to negative feedback until an acceptable improved surface design can be determined – without detriment to the surface or player.

safety needs to be revisited. It is hypothesised that there is a range of shear strength for minimum injury risk, which may or may not coincide with the optimum shear strength for surface performance. The relationship between stiffness and injury risk is different and is shown in grey in figure 4 to illustrate the lack of evidence as to whether stiff surfaces pose a greater or lower risk of injury than a compliant surface; the relationship for surface quality is more easily identified. There is also significant variation in compliance and shear strength properties among different sports surfaces.[21,91-93] The exact location of boundaries between areas in the diagram in figure 4 are not known, but are hypothesized to vary with construction material, type of sport, footwear, player characteristics and moisture content. Future research is required to identify boundary

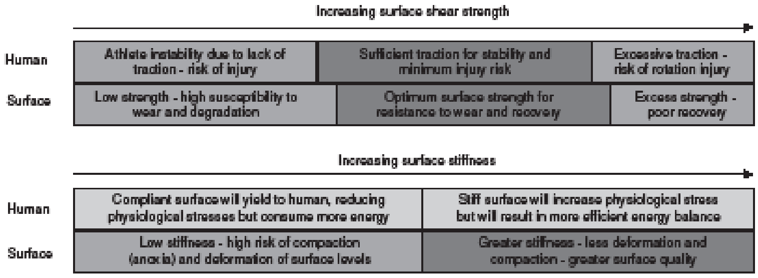


Fig. 4. A conceptual framework for natural turf research with the aim to quantify the boundaries to the shear strength and stiffness envelopes of optimum surface performance (in green) – two key mechanical properties governing player- (and ball-) surface interaction in natural turf. Red zones identify areas of risk to player or surface. Grey zones identify a particular uncertainty relating to surface stiffness and player interaction that requires further research. Note that performance is a third dimension and generally as shear strength and stiffness move towards extremes, ball-surface interactions will be adversely affected, although the same cannot be said for player performance, and both will vary with sport.

locations between areas on the diagram for different combinations of the above factors, e.g. pitch construction specification – a clay soil will have a narrower envelope of ideal traction c.f. **((Author: ok to change to 'compared with'?))** a sandy soil due to increased sensitivity of shear strength to moisture content, as discussed above **((Author: in which specific section?))**.

Initially, it will be important to obtain biomechanical data (e.g. ground reaction forces, insole pressure data and kinematic data) that enable a number of sport-specific movements performed on a natural turf surface to be characterized. Running is an integral activity for soccer, rugby, lacrosse and cricket. Additional movements that occur during these games include accelerating from rest, stopping and turning manoeuvres. During a 90-minute game of professional soccer for example, it has been stated that each player performs approximately 50 turns.[94] This activity is therefore of relevance if the nature of turf wear and degradation, and its subsequent impact on surface mechanics and player interaction, is to be understood fully.

5. Conclusions

A 'natural turf surface' encompasses a range of soil and grass materials that combine in a complex interaction that varies in space and time; to characterize a surface as natural turf is as inappropriate as to label a surface as 'artificial turf' without specifying the length of pile, the plastic material used for the fibre and the type of granular infill used for shock absorbency. Future injury studies must characterize the nature of natural turf and its variation in space and time through the study.

Complementary future research should endeavour to utilize an integrated approach using engineering and biomechanical expertise that will permit greater understanding of factors that influence natural turf wear and degradation and factors that will influence how the athlete responds to changes in natural soil media and mechanisms behind injury patterns. This is a two-way interaction that is considered to hold the key to the future development of a more sustainable natural turf surface for training and competitive use for sports whose characteristics are not suited to play on artificial turf surfaces. Furthermore, such research would inform the continued development of synthetic turf.

Acknowledgements

The assistance from Sport England and the Football Foundation is gratefully acknowledged. The authors also gratefully acknowledge funding by the Engineering and Physical Sciences Research Council, UK under project EP/C512243/1(P). **((Author: please provide information, for publication in the acknowledgements section of the manuscript, on any potential conflicts of interest that the authors may have that are directly relevant to the contents of this manuscript))**

References

1. World Health Organisation. Health and development through physical activity and sport [online]. Available from URL: whqlibdoc.who.int/hq/2003/WHO_NMH_NPH_PAH_03.2.pdf. Geneva: World Health Organization, 2003 [Accessed 2007 Nov 28]
2. Department of Health. At least five a week: evidence on the impact of physical activity and its relationship to health. Department of Health, Physical Activity, Health Improvement and Prevention 2003 [online]. Available from URL: http://www.dh.gov.uk/en/Publicationsandstatistics/Publications/PublicationsPolicyAndGuidance/DH_4080994 [Accessed 2007 Nov 28]
3. DCMS. The Government's plan for sport: a sporting future for all. Published by the Department for Culture Media and Sport (DCMS) 2001 [online]. Available from URL http://www.culture.gov.uk/Reference_library/Publications/archive_2001 [Accessed 2007 Nov 28]
4. United Nations. World urbanization prospects: the 2007 revision, executive summary. New York: Department of Economic and Social Affairs of the United Nations Secretariat, 2008
5. Foster C, Hillsdon M, Cavill N, et al. Understanding participation in sport: a systematic review. Sport England report. London: Sport England, 2005
6. Torg J, Quendenfeld T, Landau B. The shoe-surface interface and its relationship to football knee injuries. J Sports Med 1974; 2: 261-9
7. Andreasson G, Olofsson B. Surface and shoe deformation in sport activities and injuries. In: Nigg BM, Kerr BA, editors. The biomechanical aspects of sport shoes and playing surfaces. Calgary: The University of Calgary, 1983: 51-61
8. McCarthy P. Artificial turf: does it cause more injuries? Phys Sportsmed 1989; 17: 159-64
9. International Rugby Board. Regulation 22: standard relating to the use of artificial playing surfaces – IRB performance

specification for artificial surfaces for rugby. Dublin: International Rugby Board (IRB), 2008 Jan

10. FIFA. Quality concept: handbook of requirements for football turf. Geneva: Fédération Internationale de Football Association, 2006
11. Sport England. Participation in sport in England: 2002. London: English Sports Council (Sport England), 2002
12. Spencer M, Lawrence S, Rechichi M, et al. Time motion analysis of elite field hockey, with special reference to repeated-sprint activity. J Sports Sci 2004; 22: 843-50
13. Kolitzus HJ. Functional standards for playing surfaces. In: Frederick EC, editor. Sport shoes and playing surfaces: biomechanical properties. Champaign (IL): Human Kinetics Pubishers Inc., 1984: 98-118
14. Nigg BM, Yeadon MR. Biomechanical aspects of playing surfaces. J Sports Sci 1987; 5: 117-45
15. Cox AL. Test methods for assessing the performance of sports surfaces. In: Nigg BM, Cole GK, Stefanyshyn DJ, editors. Sports surfaces. Calgary: The University of Calgary, 2003: 269-91
16. Baker S. Temporal variation of selected mechanical properties of natural turf football pitches. J Sports Turf Res Inst 1991; 67: 83-92
17. James IT, Blackburn DWK, Godwin RJ. Mole drainage as an alternative to sand slitting in natural turf sports surfaces on clays. Soil Use Manage 2007; 23: 28-35
18. James IT, Hann MJ, Godwin RJ. Design and operational considerations for the use of mole ploughing in the drainage of sports pitches. Biosyst Eng 2007; 97: 99-107
19. McLeod AJ. An assessment of the benefits of artificial turf over natural turf playing surfaces within the independent school environment. [dissertation]. Cranfield: Cranfield University, 2003
20. NPFA. The six-acre standard. London: National Playing Fields Association, 2001
21. Baker SW, Cook A, Adams WA. Soil characteristics of first-class cricket pitches and their influence on playing performance. J Turfgrass Sci 1998; 74: 63-79
22. Grace J. The effect of wind on grasses. J Exp Botany 1974; 25: 542-51
23. Meyers MC, Barnhill BS. Incidence causes and severity of high school football injuries on fieldturf versus natural grass. Am J Sports Med 2004; 32: 1626-38
24. Fuller CW, Dick RW, Corlette J, et al. Comparison of the incidence, nature and cause of injuries sustained on grass and new generation artificial turf by male and female football players. Part 1: match injuries. Br J Sports Med 2007; 41 SI: i20-6
25. Fuller CW, Dick RW, Corlette J, et al. Comparison of the incidence, nature and cause of injuries sustained on grass and new generation artificial turf by male and female football players. Part 2: training injuries. Br J Sports Med 2007; 41 SI: i27-32
26. Ekstrand J, Timpka T, Hägglund M. Risk of injury in elite football played on artificial turf versus natural grass: a prospective two-cohort study. Br J Sports Med 2006; 40: 975-80
27. Steffen K, Andersen TE, Bahr R. Risk of injury on artificial turf and natural grass in young female football players. Br J Sports Med 2007; 41 SI: i33-7
28. Martinez A, Dura JV, Duenas L, et al. Artificial and natural turf: biomechanical differences between surfaces. Communications of the Fifth World Congress on Science and Football. J Sports Sci 2004; 22: 494-5
29. Dick RW, Schmalz R, Diehl N, et al. A review of game injuries by surface and injury mechanism in NCAA intercollegiate sports. In: Nigg BM, Cole GK, Stefanyshyn DJ, editors. Sports surfaces. Calgary: The University of Calgary, 2003: 107-23
30. Adams WA, Stewart VI, Thornton DJ. The assessment of sands suitable for use in sportsfields. J Sports Turf Res Inst 1971; 47: 77-85
31. Zamparo P, Perini R, Orizio C, et al. The energy cost of walking or running on sand. J Eur J Appl Physiol 1992; 65: 183-7
32. Reilly T. Science and football: a history and an update. In: Reilly T, Cabri J, Araujo D, editors. Science and football V. Oxon: Routledge, 2005: 3-12
33. Bonstingl RW, Morehouse CA, Nichol B. Torques developed by different types of shoes on various playing surfaces. Med Sci Sports 1975; 7: 127-31
34. Brown RP. Performance tests for artificial sports surfaces. Polym Test 1987; 7: 279-92
35. Valiant GA. Transmission and attenuation of heel strike accelerations. In: Cavanagh PR, editor. Biomechanics of distance running. Champaign (IL): Human Kinetics, 1990: 225-47
36. Dixon SJ, Batt ME, Collop AC. Artificial playing surfaces research: a review of medical, engineering and biomechanical aspects. Int J Sports Med 1999; 20: 209-18
37. Stiles VH, Dixon SJ. The influence of different playing surfaces on the biomechanics of a tennis running forehand foot plant. J Appl Biomech 2006; 22: 14-24
38. Coyles VR, Lake MJ, Patritti BL. Comparative evaluation of soccer boot traction during cutting manoeuvres: methodological considerations for field testing. In: Haake SJ, editor. The engineering of sport. Cambridge: Blackwell Science, 1998: 183-90
39. Coyles VR, Lake MJ. Forefoot plantar pressure distribution inside the soccer boot during running. Proceedings of the International Society of Biomechanics Footwear Biomechanics Group; 1999 Aug 5–7; Canmore
40. Morag E, Johnson DA. Traction requirements of young soccer players [abstract]. In: Hennig E, Stacoff A, editors. Proceedings of the Symposium on Footwear Biomechanics; 2001 Jul 5–7; Zurich, 62-3
41. Eils E, Streyl M, Linnenbecker S, et al. Characteristic plantar pressure distribution patterns during soccer-specific movements. Am J Sports Med 2004; 32: 140-5
42. James SL, Bates BT, Osternig LR. Injuries to runners. Am J Sports Med 1978; 6: 40-50
43. Cavanagh PR, LaFortune MA. Ground reaction forces in distance running. J Biomech 1980; 13: 397-406
44. Light LH, MacLellan GE, Klenerman L. Skeletal transients on heel strike in normal walking with different footwear. J Biomech 1979; 13: 477-80
45. Frederick EC, Clarke TE, Hamill CL. The effect of running shoe design on shock attenuation. In: Frederick EC, editor. Sports shoes and playing surfaces. Champaign (IL): Human Kinetics, 1984: 190-8

46. Nigg BM, Frederick EC, Hawes MR, et al. Factors influencing short-term pain and injuries in tennis. Int J Sport Biomech 1986; 2: 156-65
47. Miller DI. Ground reaction forces in distance running. In: Cavanagh PR, editor. Biomechanics of distance running. Champaign (IL): Human Kinetics, 1990: 203-23
48. Hamill J, Bates BT, Holt KG. Timing of lower extremity joint actions during treadmill running. Med Sci Sports Exerc 1992; 24: 807-13
49. Stergiou N, Bates BT. The relationship between subtaler and knee joint function as a possible mechanism for running injuries. Gait Posture 1997; 6: 177-85
50. Richie DH, DeVries HA, Endo CK. Shin muscle activity and sports surfaces: an electromyographical study. J Am Podiatr Med Assoc 1993; 83: 181-90
51. Stucke H, Baudzus W, Baumann W. On friction characteristics of playing surfaces. In: Frederick EC, editor. Sports shoes and playing surfaces. Champaign (IL): Human Kinetics, 1984: 87-97
52. Nigg BM, Denoth J. *Sportplatzbelaege (playing surfaces)*. Zurich: Juris Verlag, 1980
53. Nigg BM, Segesser B. The influence of playing surfaces on the load on the locomotor system and on football and tennis injuries. J Sports Med 1988; 5: 375-85
54. Nigg BM, Cole GK, Stefanyshyn DJ. Impact forces during exercise and sport activities. In: Nigg BM, Cole GK, Stefanyshyn DJ, editors. Sports surfaces. Calgary: The University of Calgary, 2003: 13-29
55. Basthoit P. Professional tennis (ATP tour) and number of medical treatments in relation to type of surface. Med Sci Tennis 2000; 5(**(Author: please supply volume, issue and page numbers)**)
56. Orchard J. Is there a relationship between ground and climatic conditions and injuries in football. J Sports Med 2002; 32: 419-32
57. Canaway PM, Bell MJ, Holmes G, et al. Standards for the playing quality of natural turf for association football. In: Schmidt RC, Hoerner EF, Milner EN, et al., editors. Natural and artificial playing fields: characteristics and safety features. Philadelphia (PA): ASTM, 1990: 29-47
58. Orchard J. The AFL Penetrometer study: work in progress. J Sci Med Sport 2001; 4: 220-32
59. Garcia AC, Martinez A, Solaz JS, et al. Development of a method for measuring horizontal forces in soccer boots studs during skills performance. Proceedings of the International Society of Biomechanics Footwear Biomechanics Group; 1999 Aug 5-7; Canmore
60. Milburn PD, Barry EB. Shoe-surface interaction and the reduction of injury in rugby union. J Sports Med 1998; 25: 319-27
61. Livesay GA, Reda DR, Nauman EA. Peak torque and rotational stiffness developed at the shoe-surface interface: the effect of shoe type and playing surface. Am J Sports Med 2006; 34: 415-22
62. Lambson RB, Barnhill BS, Higgins RW. Football cleat design and its effect on anterior cruciate ligament injuries: a three-year prospective study. Am J Sports Med 1996; 24: 155-9
63. Carré MJ, Kirk RF, Haake SJ. Developing relevant tests for traction of studded footwear on surfaces. In: Fleming P, Young C, Dixon S, et al., editors. STARSS 2007. Proceedings of the First International Conference of the SportSURF Network; 2007 Sep 17-18; Loughborough: Loughborough University(**(Author: please supply page numbers)**)
64. Orchard J, Chivers IH, Aldous DE, et al. Rye grass is associated with fewer non-contact anterior cruciate ligament injuries than Bermuda grass. Br J Sports Med 2005; 39: 704-9
65. Chivers IH, Aldous DE, Orchard J. The Relationship of Australian Football grass surfaces to anterior cruciate ligament injury. Int Turfgrass Soc Res J 2005; 10: 327-32
66. Hodgson Phillips L, Standen PJ, Batt ME. Effects of seasonal change in rugby league on the incidence of injury. Br J Sports Med 1998; 32: 144-8
67. Fleming PR, Young C, Roberts JR, et al. Human perceptions of artificial surfaces for field hockey. Sports Eng 2005; 8: 121-36
68. Canaway PM. Fundamental techniques in the study of turfgrass wear: an advance report on research. J Sports Turf Res Inst 1975; 51: 104-15
69. Canaway PM, Bell MJ. Technical note: an apparatus measuring traction and friction on natural and artificial playing surfaces. J Sports Turf Res Inst 1986; 62: 211-4
70. Andreasson G, Lindenberger U, Renstrom P, et al. Torque developed at simulated sliding between sports shoes and an artificial turf. Am J Sports Med 1986; 14: 225-9
71. McNitt AS, Middour RO, Waddington DV. Development and evaluation of a method to measure traction on turf surfaces. J Test Eval 1997; 25: 99-107
72. Blackburn S, Nicol A, Walker C. Development of a biomechanically validated turf testing rig. In: Proceedings of the International Society of Biomechanics XXth Congress – ASB 29th Annual Meeting; 2005 Jul 31-Aug 5; Cleveland
73. FIH. Handbook of performance requirements and test procedures for synthetic hockey pitches: outdoor. Lausanne: Federation Internationale de Hockey, 1999
74. ITF. Court surface classification scheme. London: International Tennis Federation, 2000
75. Young C, Fleming PR. A review of mechanical impact testing devices for sport surfaces. In: Fleming P, Young C, Dixon S, et al., editors. STARSS 2007. Proceedings of the First International Conference of the SportSURF Network; 2007 Sep 17-18. Loughborough: Loughborough University(**(Author: please supply page numbers)**)
76. Dabnichki P. Force measurement and calculation in sport activities. In: Haake SJ, editor. The engineering of sport. Cambridge: Blackwell Science, 1998: 317-24
77. Lafortune MA, Morag E, Pisciotta J. Sports surface and athletic footwear creation. In: Nigg BM, Cole GK, Stefanyshyn DJ, editors. Sports surfaces. Calgary: The University of Calgary, 2003: 217-32
78. Smith N, Dyson R, Hale T. The effects of sole configuration on ground reaction force measured on natural turf during soccer specific actions. In: Spinks W, Reilly T, Murphy A, editors. Science and football IV. London: Routledge, 2002: 44-9
79. Smith N, Dyson R, Janaway L. Ground reaction force measures when running and jogging in soccer boots and

soccer training shoes on a natural turf surface. Sports Eng 2004; 7: 159-67

80. Tillman MD, Fiolkowski P, Bauer JA, et al. In-shoe plantar measurements during running on different surfaces: changes in temporal and kinetic parameters. Sports Eng 2002; 5: 121-8
81. Ford KR, Manson NA, Evans BJ, et al. Comparison of in-shoe loading patterns on natural grass and synthetic turf. J Sci Med Sport 2006; 9: 433-40
82. Dixon SJ, James IT, Blackburn DWK, et al. Influence of footwear and soil density on loading within the shoe and soil surface during running. Proceedings of the Institution of Mechanical Engineers, part P. J Sports Eng Technol. In press((**Author: please update details if this has since been published**))
83. Gonzalez JC, Martinez A, Montero J, et al. Analysis of the horizontal force in soccer boot studs for specific movements. In: Proceedings of the ISB Footwear Biomechanics Group; 2008 Jul 3–5; Queenstown
84. Shorten M, Hudson B, Himmelsbach J. Shoe-surface traction of conventional and in-filled synthetic turf football surfaces. In: Proceedings of International Society of Biomechanics XIXth Congress; 2003 Jul 6-11; Dunedin, 360
85. Brachet P, Blackburn S, Nicol AC, et al. Body and limb accelerations during football activities on artificial turfs [abstract]. In: Proceedings of the International Society of Biomechanics XIXth Congress; 2003 Jul 6-11; Dunedin, 39
86. Stiles VH, Dixon SJ, Guisasola IN, et al. Kinematic response to variations in natural turf during running. In: Moritz EF, Haake S, editors. The engineering of sport 7. 2008. In press((**Author: please update details if this has since been published**))
87. Blackburn S, Brachet P, Nicol AC, et al. Player/ground interaction on artificial turf. In: Proceedings of the International Society of Biomechanics XIXth Congress; 2003 Jul 6-11; Dunedin, 34
88. Stiles VH, Dixon SJ, James IT. An initial investigation of human-natural turf interaction in the laboratory. In: Moritz EF, Haake S, editors. The engineering of sport 6. Vol 2. New York: Springer, 2006: 255-60
89. Stiles VH, Dixon SJ, Guisasola IN, et al. Biomechanical response to variations in natural turf surfaces during running and turning. In: Fleming P, Young C, Dixon S, et al. STARSS 2007. Proceedings of the First International Conference of the SportSURF Network. 2007 Sep 17-18; Loughborough: Loughborough University((**Author: please supply page numbers**))
90. James IT, Waine TW, Bradley RI, et al. Determination of soil type boundaries using electromagnetic scanning techniques. Biosyst Eng 2003; 86: 421-30
91. Canaway PM. The response of Lolium perenne turf grown on sand and soil to fertilizer nitrogen III: aspects of playability – ball bounce resilience and shear strength. J Sports Turf Res Inst 1984; 60: 27-36
92. Baker SW. The reinforcement of turfgrass areas using plastic and other synthetic materials: a review. Int Turf Soc Res J 1997; 8: 3-13
93. McNitt AS, Landschoot PJ. Effects of soil reinforcing materials on the surface hardness, soil bulk density and water content of a sand root zone. Crop Sci 2003; 43: 957-66
94. Withers RT, Maricic Z, Wasilewski S, et al. Match analysis of professional Australian soccer players. J Hum Mov Stud 1982; 8: 159-76

Correspondence: Dr *Victoria H. Stiles*, School of Sport and Health Sciences, St Luke's Campus, University of Exeter, Heavitree Road, Exeter, EX1 2LU, UK.((**Author: Please provide e-mail address of the corresponding author**))